Lecture Notes in Mobility

Ciaran McNally · Páraic Carroll · Beatriz Martinez-Pastor · Bidisha Ghosh · Marina Efthymiou · Nikolaos Valantasis-Kanellos *Editors*

Transport Transitions: Advancing Sustainable and Inclusive Mobility

Proceedings of the 10th TRA Conference, 2024, Dublin, Ireland - Volume 3: Eco-efficient Mobility Systems

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Lecture Notes in Mobility

The book series Lecture Notes in Mobility (LNMOB) reports on innovative, peer-reviewed research and developments in intelligent, connected and sustainable transportation systems of the future. It covers technological advances, research, developments and applications, as well as business models, management systems and policy implementation relating to: zero-emission, electric and energy-efficient vehicles; alternative and optimized powertrains; vehicle automation and cooperation; clean, user-centric and on-demand transport systems; shared mobility services and intermodal hubs; energy, data and communication infrastructure for transportation; and micromobility and soft urban modes, among other topics. The series gives a special emphasis to sustainable, seamless and inclusive transformation strategies and covers both traditional and any new transportation modes for passengers and goods. Cutting-edge findings from public research funding programs in Europe, America and Asia do represent an important source of content for this series. PhD thesis of exceptional value may also be considered for publication. Supervised by a scientific advisory board of world-leading scholars and professionals, the Lecture Notes in Mobility are intended to offer an authoritative and comprehensive source of information on the latest transportation technology and mobility trends to an audience of researchers, practitioners, policymakers, and advanced-level students, and a multidisciplinary platform fostering the exchange of ideas and collaboration between the different groups.

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Preface

We are pleased to publish the Conference Proceedings of the 10th Transport Research Arena (TRA 2024), held on April 15–18 2024 in Dublin, Ireland. The conference brought together 4500 delegates from 57 countries who came together to discuss research findings, the latest innovations in policy, technology and practice, and the future directions of mobility and transport.

The conference tagline was *Transport Transitions: Advancing Sustainable and Inclusive Mobility*, and four primary conference themes were defined, namely:

- Safe & Inclusive Transport
- Sustainable Mobility of People and Goods
- Efficient & Resilient Systems
- Collaborative Digitalization

TRA takes place every 2 years, and TRA2024 featured an array of plenary sessions, ministerial sessions, strategic sessions and special sessions which took place alongside the technical programme. A call for papers was issued in early 2023 which resulted in 1182 submissions. A double blind peer review process was initiated, which ultimately resulted in 784 papers that were chosen for presentation at the conference (66% conversion rate). These papers were presented in a combination of oral or poster presentations over the course of the conference.

All accepted papers presented at TRA 2024 are published in a topical collection of the journal European Transport Research Review (ETRR) or within these proceedings. Both are published in a fully open access format.

TRA is a multi-modal conference that draws on the support of key stakeholders. These include the European Commission, ACARE (Advisory Council for Aviation Research and Innovation in Europe), ALICE (Alliance for Logistics Innovation through Collaboration in Europe), CEDR (Conference of European Road Directorates), ECTP (European Construction Technology Platform), ERRAC (European Rail Research Advisory Council), ERTRAC (European Road Transport Research Advisory Council), ETRA (European Transport Research Alliance), and the Waterborne technology platform. Key Irish supporters of the event were Transport Infrastructure Ireland, Enterprise and Ireland and the Irish Government's Department of Transport.

The editors would like to express their thanks to the presenters, authors, reviewers, session chairs, committee members and sponsors for helping deliver such a successful event. TRA 2026 will take place in Budapest, Hungary.

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Contents

Zero Emissions Transport

Are Academics' Willing to Change Their Conference Travel Habits for the Sake of the Environment? – The Case of Spain

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Abstract. As concerns about climate change increase, the environmental impact of long-distance travel – including academic conference travel – is coming into focus. Multiple universities have recently started to deploy sustainability policies committed to net-zero targets. However, it remains uncertain today whether academics are ready to embrace such initiatives and transform their practices for the sake of the environment. In this study, we explore the motivational factors behind academics' willingness to limit their conference travel based on a survey conducted in Spain. The results highlight the role played by a set of demographic, socioeconomic, work-related, and attitudinal factors, as estimated by means of an ordered logit model. All else being equal, postdoctoral researchers and individuals who live in single-person households are more likely than others to reduce their travel. In terms of psychological attributes, we detect that individuals with a higher level of green values and more influenced by social norms are more intended to limit their conference trips. Conversely, those who believe that conferences are a driver for professional development are less willing to lower their travel. Our findings can help institutions to identify the segments of academics with a higher (and lower) probability of changing their behaviour towards more sustainable habits.

Keywords: Conference travel · Behavioural change · Climate change

1 Introduction

As concerns about climate change increase, the environmental impact of long-distance travel – and particularly, air travel – is coming into focus. Nowadays, the avion industry is responsible for approximately 13% of greenhouse gas (GHG) emissions from the transport sector and 2% of total anthropogenic GHG emissions [1].

Air travel and aeromobility are culturally at the core of academic life. Academics are often engaged in a wide variety of activities that involve this practice. Among them, attending conferences is considered central [2]. Not only do they provide the appropriate framework for presenting and disseminating one's own work to interested colleagues, but

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they are also important settings for establishing (international) collaborations, exchanging knowledge, and building professional networks, among other possibilities. In a globally competitive scenario, conference attendance is seen as a driver for achieving a successful academic career.

However, despite all these opportunities, attending academic conferences is also a carbon-emitting activity [3]. As a result, there is an active and growing debate on the necessity to limit this academic mobility. The environmental impacts arising from conference travel have become a priority issue for the sustainability programmes of numerous universities and research centres. In recent years, these institutions have started to define and deploy policies committed to net-zero targets. Today, although these initiatives aim to encourage more sustainable behaviours among the academic community, it remains uncertain whether individuals are ready to embrace them (for the sake of the environment) and modify their practices. Experts agree that these initiatives to limit the negative effects of conference travel require the involvement and compromise of academics themselves, who should be eager to contribute by changing their conducts.

As highlighted by [4], understanding the factors behind academics' willingness to limit their mobility is key to design effective strategies that influence individuals' decision-making processes towards "greener" habits. Previous literature recognises three main groups of explanatory variables: demographic and socioeconomic attributes, work-related characteristics, and personal attitudes and preferences. Nevertheless, to our knowledge, quantitative research on academics' motivations for reducing their conference travel is still scarce and further investigation is therefore required. This study explores the factors that underpin academics' willingness to reduce their conference travel for the sake of the environment, focusing on the Spanish academic community. Our findings can help universities and research institutions to understand which academic profiles are more (or less) likely to transform their current behaviours for environmental reasons.

2 Methodological Approach

2.1 Survey Design and Data Collection

In this paper, we examine academics' willingness to reduce their conference travel. With this objective, we design a tailor-made survey aimed at identifying a set of explanatory variables determining each individual's intention to change behaviour. Specifically, we consider demographic, socioeconomic, work-related, and attitudinal variables. Based on a detailed review of previous questionnaires with a similar scope, we structure the survey in five parts:

- Part I. Conference travel habits: number of conferences attended per year.
- Part II. Academics' personal attitudes. Based on the review of earlier literature, we select seven factors (environmental concerns, bringing benefits to the scientific community, joy of travelling, personal performance and development, importance of face-to-face interactions, social norms on travel reduction, and ethical responsibility of academics) that might explain academics' willingness to reduce their conference travel for environmental motives. To operationalise these (latent) factors, we adopt

and adapt validated items from prior research. For all the items, respondents are requested to rate their level of agreement on a 7-point Likert-type scale, ranging from "strongly disagree" to "strongly agree".
- Part III. Individuals are directly asked to rate – on a 7-point Likert-type scale – their willingness to reduce their conference travel for the sake of the environment. This represents our dependent variable.
- Part IV. Work-related variables: research field, academic position at university, and effects of the COVID-19 pandemic on (work) travel habits.
- Part V. Demographic and socioeconomic characteristics (gender, age, etc.).

The questionnaire was distributed online between the 15^{th} of June and the 15^{th} of September 2023, targeting academics based in Spain. For the sample recruitment, we combined the following two approaches: (1) distribution of flyers (which included a web-link and a QR code to the questionnaire) during an international conference related to the transport field that was held in Spain, and (2) dissemination of the questionnaire through social media. Prior to the final survey, a pilot survey was conducted.

2.2 Analysis of the Survey Outputs

The analysis of the data collected through the online survey comprises three steps. First, a descriptive analysis is developed. Second, an Explanatory Factor Analysis (EFA) is conducted to identify the latent structure underlying the set of attitudinal variables measured through the questionnaire (Part II). And third, the factorial structure revealed is used to develop a discrete choice experiment based on logit specifications. Particularly, given the ordered and discrete nature of the dependent variable, we apply an ordered logit (O-Logit) model to examine the explanatory factors determining academics' willingness to reduce their conference travel for the sake of the environment (Part III of the survey). This methodological approach has been extensively used in transport studies to explore individuals' intentions and behaviours. [5] note the assumption of proportional odds in O-Logit models, according to which the relationship between any pair of outcome categories is assumed to be equal. Therefore, in this investigation, the six cumulative odds ratios obtained from the ordinal measure of the seven levels of willingness are considered identical.

3 Modelling Results and Findings

By September 2023, a total of 208 valid responses were collected. While the sample is not fully representative of the Spanish academic community, it includes a sufficient level of heterogeneity for our modelling purposes.

3.1 Descriptive Analysis: Academics' Willingness to Change Their Habits

In the third part of the survey, individuals are specifically asked to rate their willingness to reduce their conference travel. In general, our results show a positive predisposition on the part of the Spanish academic community: almost a 30% of the individuals reported a 'high' or 'very high' intention of limiting their travel (see Fig. 1).

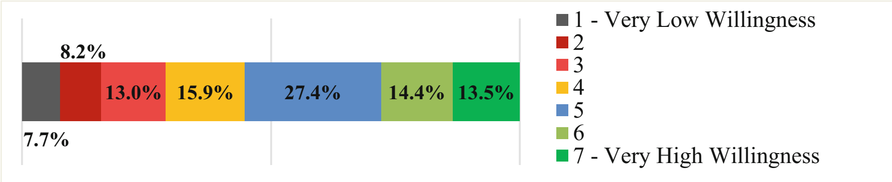

Fig. 1. Part III of the survey: "Are you willing to reduce your conference travel for the sake of the environment?". To answer on a 7-point Likert-type scale: 1 (minimum) – 7 (maximum).

3.2 Exploratory Factor Analysis (EFA)

An EFA is conducted to explore the latent structure underlying the set of attitudinal variables measured through the online survey (Part II), using the SPSSv29 software package. A preliminary analysis of the descriptive statistics reports a good internal consistency of the data and a good sample adequacy. The determinant of the Spearman's correlation matrix shows the absence of multi-collinearity, and the Bartlett's test for sphericity rejects the null hypothesis of an identity correlation matrix. Principal Axis Factoring (PAF), with orthogonal 'Varimax' rotation, uncovers seven attitudinal factors (see Table 1), which correspond to those addressed through the questionnaire (Sect. 2.1). Orthogonal rotation ensures that the latent factors are uncorrelated [6]. The explained cumulative variance of the revealed factors accounts for over 65%, so the underlying structure can be accepted.

Based on the "two-indicator rule" [7], the analysis considers at least two items per factor, and 0.50 is set as the cut-off value to retain the items. The factorial structure obtained is used to develop the subsequent O-Logit model.

Table 1. Rotated factor matrix for attitudinal factors.

Factor (F)	Description	(α)
F1	Environmental concerns	0.890
F2	Bringing benefits to the scientific community	0.854
F3	Joy of travelling	0.834
F4	Personal performance and development	0.735
F5	Importance of face-to-face interactions	0.770
F6	Social norms on travel reduction	0.734
F7	Ethical responsibility of academics	0.732
Cronbach's alpha (α) = 0.785; Kaiser-Meyer-Olkin (KMO) = 0.810; p = 0.000		

3.3 Ordered Logit (O-Logit) Model: Results and Discussion

As a final step, we apply an O-Logit Model to investigate academics' willingness to reduce their conference travel for the sake of the environment in Spain. As mentioned in

Sect. 2, this study focuses on a set of demographic and socioeconomic, work-related, and attitudinal characteristics. First, we develop a series of tests for checking multicollinearity among all the (potential) explanatory variables, and no significant interactions are identified [8]. Then, we run the O-Logit model through the Stata software (version 17). Given that some of the explanatory variables included in the model are categorical, it is necessary to define a base case as a reference to interpret the modelling results correctly (see Table 2). This allows us to determine whether individuals' answers are statistically significant when compared to the base case.

The O-Logit model confirms that, from a statistical viewpoint, academics' willingness to reduce their conference travel for the sake of the environment is determined by a series of demographic and socioeconomic, work-related, and attitudinal variables.

In terms of personal attributes, household structure is the only variable that appears to be significant. We find that, all else being the same, those academics living alone are more likely than others to lower their conference travel for the benefit of the environment. Meanwhile, work-related characteristics seem to play a major role in explaining academics' intention to reduce conference travel. In addressing the influence of the academic position, we recognise that postdoctoral researchers are the most willing to limit their business trips. Our modelling results also show that academics who attend conferences on an annual basis (within Europe) are less likely to limit their conference travel than those who do not attend any conferences. This is consistent with previous investigations that argue that established travel habits are strong constraints to reducing people's mobility [9]. In addition, the impact of the COVID-19 also appears to be significant: academics whose work practices were affected by the pandemic show a greater willingness to reduce their conference travel than those who were not affected. Finally, other two travel-related aspects result relevant. On the one hand, we detect that academics' motivation to travel for meeting new people and visiting new places is indirectly linked with their willingness to lower their trips. On the other hand, the model points out that academics' eagerness to maintain an appropriate work-life balance is directly correlated with their willingness to reduce travelling. In terms of psychological factors, we observe that academics with a higher level of environmental values and who are more influenced by social norms (of travel reduction) are more intended to limit their conference travel. On the contrary, those who believe that conferences are a driver for professional development are less willing to lower their trips for environmental reasons. Unexpectedly, the other four attitudinal factors obtained after conducting the EFA are not significant.

All these findings can assist institutions in foreseeing the segments of academics with a higher (and lower) probability of shifting their behaviour in coming years. This approach is key to comprehensively understand individuals' intentions as a critical step towards the definition of sustainability policies that support a system-wide transformation of practices at the institutional level. Individual changes will only happen if academia at large moves forward in the same direction.

Table 2. Modelling results (O-Logit): Academics' willingness to reduce their conference travel.

-[1]	Variable		Coeff	Std. Error	p-value
D/S	Gender	*Base case: Male*			
		Female	.113	.278	0.685
	Household composition	*Base case: Other*[2]			
		Alone	.485	.357	0.075
W	Academic position at university	*Base case: Other*[3]			
		Post-doctoral researcher	−.680	.300	0.023
	Work involves solving environmental issues	*Base case: No*			
		Yes	.195	.302	0.517
	Travel habits affected by the COVID-19	*Base case: No*			
		Yes	.153	.068	0.026
	Conference attendance on an annual basis[4]	*Base case: No*			
		Yes	−.647	.353	0.067
	Motivation for attending conferences: enjoy meeting new people and visiting new places	–	−.425	.112	0.000
	Motivation for (not) attending conferences: eagerness to maintain an appropriate work-life balance	–	.349	.155	0.024
A	Environmental concerns		1.017	.144	0.000
	Personal performance		−.232	.131	0.078
	Social norms		.405	.102	0.000
	Ethical responsibility		.182	.145	0.207

Number of observations: 208; Log-Likelihood at convergence: −310.818; Log-Likelihood restricted: −387.517; Mc Fadden's Pseudo R^2: 0.1979

[1]D/S: demographic and socioeconomic attributes; W: work-related characteristics; A: attitudinal factors. [2]With roommates/friends, with parents, with partner/spouse, with partner/spouse and child/children, with child/children (single parent). [3]Student, pre-doctoral researcher, and professor. [4]Within Europe

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Decarbonizing Maritime Corridors: How Carbon-Neutral Shipping Creates Environmental, Economic, and Social Impacts

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Abstract. There is increasing pressure to reduce greenhouse gas (GHG) emissions in the transport sector, with a specific focus on maritime transportation. Green maritime corridors, originally introduced in the Clydebank Declaration, represent a bottom-up approach for potentially effective decarbonization of maritime transportation. The premise of the research presented in this paper is that such initiatives, involving numerous actors in a logistics value chain, can have a more significant impact than merely reducing GHG emissions from sea transportation. In this paper, we present an impact assessment framework for decarbonizing maritime corridors in the context of RoPax (passenger and vehicle) shipping. We have identified 17 impacts, including the impacts on negative externalities, socio-economic impacts, impacts on transportation, and enabling effects on other industries in terms of the green transition. The Turku–Stockholm (Finland–Sweden) RoPax shipping corridor serves as a case study, considering a scenario in which one shipping line operator transitions from fossil LNG to e-methane as the primary fuel for the two ships operating on the route, along with the installation of batteries for power balance during voyages and while in the harbour area.

Keywords: Impact assessment · Green transition · RoPax shipping · Shipping corridor · Sustainability

1 Introduction

We study what kind of sustainability impacts are generated as two RoPax (roll-on, roll-off passenger vessel) ships on a specific route from Finland to Sweden switch from fossil marine fuels (LNG) to environmentally sustainable but more expensive carbon-neutral e-methane. We present a framework for a holistic impact assessment of decarbonizing maritime corridors with a focus on RoPax shipping, covering both direct and indirect business opportunities, environmental gains and socio-economic benefits. We apply this framework to a RoPax corridor to demonstrate the benefits for different stakeholders along the value system and discuss the wider impact of establishing green maritime

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corridors on green transition beyond sea logistics. Altogether, 17 different impacts were identified based on a review of various transport project assessments, interviews with key stakeholders and a conducted analysis of current body of knowledge on green maritime corridors. From the economic or business perspective, impacts on gross domestic product, employment, cost of transportation, and value of transported goods are assessed. As regards social aspects, the possible changes in safety and health impacts were taken into consideration. We also attempt to embed the enabling impact on the sustainability transition by assessing the impacts on green tourism and green manufacturing.

2 Literature Overview – Green Maritime Corridors

Transport corridors are transport networks that enable access and can facilitate faster, smoother and more efficient transit and improve connectivity [1, 2]. Transport corridors can be domestic or international. They may be unimodal, that is, including only one transportation mode (e.g. road) or multimodal including both land- and sea-based transportation. Maritime corridors refer to corridors involving only maritime transport, typically between two or more ports. The concept of 'green maritime corridors' was initially conceptualized by the Getting To Zero Coalition [3] and announced publicly during the COP 26 Climate conference in Glasgow in 2021 as part of the Clydebank Declaration [4]. The concept is still evolving and hence there are also several different definitions of what constitutes a 'green maritime corridor'. We adopt the definition by the Global Maritime Forum and Getting to Zero Coalition [5], as it underlines the various aspects of feasibility of such initiatives:

> "Specific shipping routes where the technological, economic and regulatory feasibility of the operation of zero-emission ships is catalyzed by a combination of public and private actions."

3 Materials and Methods

This research was conducted as part of the DECATRIP project, which main task was to assess the feasibility of a scenario where a RoPax ship operator on the Turku-Stockholm route transitions from fossil fuels to carbon-neutral e-methane, which costs two to three times more than the fuels it previously used. Following the critique of sustainability assessment methods as regards their utility for assessing new ventures [6], we approached the task of developing an assessment framework for green corridors by synthesizing the existing body of knowledge on such frameworks with the contextual knowledge of the case at hand. We reviewed a number of impact assessment methods in transportation and energy industry, conducted interviews with project stakeholders and drew on statistical data from Finnish Customs [7] and Finnish Transport and Communications Agency [8].

4 Results

The impact assessment framework is visualized in Fig. 1 and is further elaborated in this section. Assessing the impacts of green maritime corridors is crucial for predicting the possible outcomes for the different stakeholders along the value chain. The impacts range from direct impacts of a project aimed at decarbonizing a maritime corridor to more indirect or long-term effects that affect other connected industries and society at large. We emphasize the impact of establishing a green corridor on the transportation industry. This influence goes beyond sea transportation, extending to entire supply chains that can benefit from sustainable transportation.

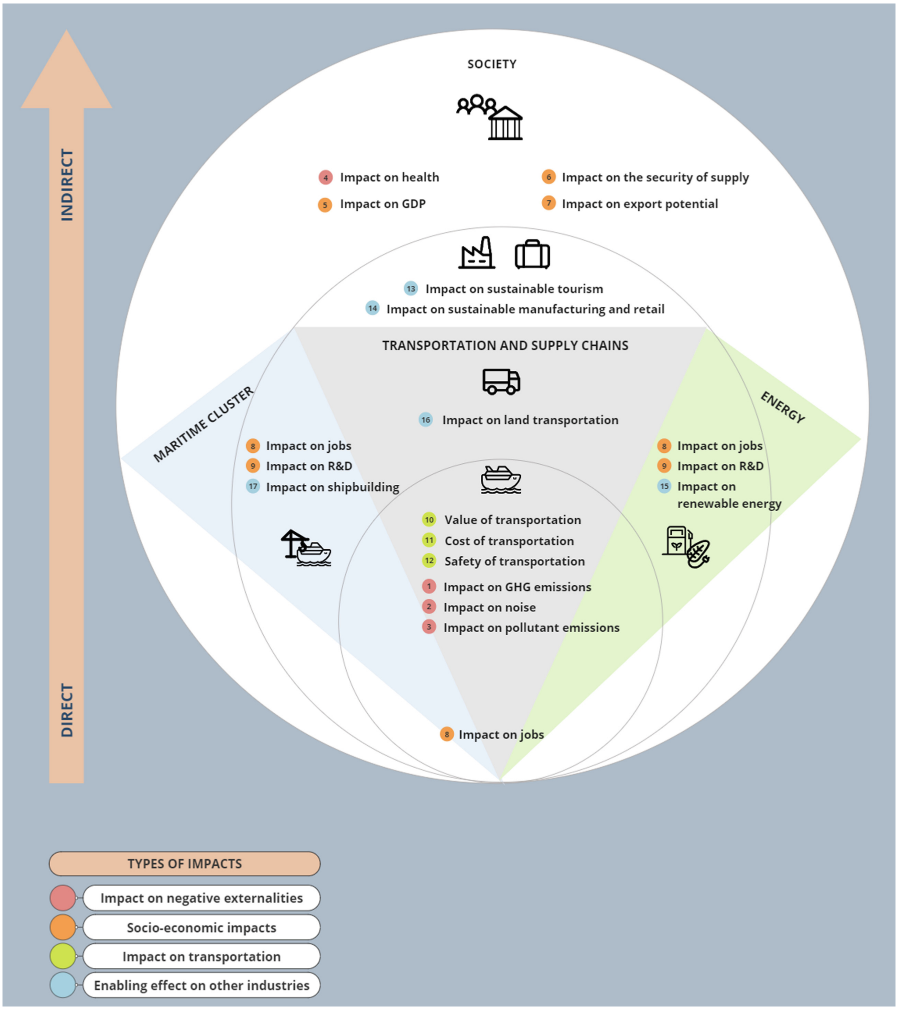

Fig. 1. Sustainability impacts in relation to decarbonized shipping corridor. (Source: authors)

Further, green corridors can also trigger changes in the shipbuilding industry and energy markets. We further explicate the logic for assessing each of the impacts presented in Fig. 1, using the case corridor and scenario for decarbonization.

Impact on GHG Emissions (1)
The core of the transition considering the green corridor is the change from a fossil fuel (LNG) to liquefied e-methane. This change can be done without retrofitting the vessel, since LNG is nearly 100% methane. However, the pilot fuel used to support the combustion process of methane has to be changed to biodiesel, in order the corridor shall be fully decarbonized. Full reduction is not achieved due to the methane slip, which means that unburned methane leaks out of the fuel system to the atmosphere.

Impact on Noise (2)
A hybrid configuration to ship propulsion design assumed in this scenario means batteries will be installed on the side of the electricity generators. Thus, the ships can manoeuvre to the ports without a need to utilize methane engines. The battery also helps in electricity generation during the intervals when high amounts of power is needed. The use of the battery makes the ship more silent when approaching the ports.

Impact on Pollutant Emissions (3)
In addition, the usage of the battery reduces pollutant emissions close to zero, when the ship is approaching ports. The battery also reduces the need for the peak performance of the methane engine and the generators. Altogether, 3% of the fuel consumption can be reduced by using the battery, which leads to reduction of pollutant emissions such as SOx, NOx, and particulate matter emissions.

Impact on Health (4)
Pollutant emissions, such as SOx, NOx, and particulate matter emissions, cause health problems, and due to the aid of battery at ports, less pollutant emissions are generated.

Impact on GDP (5)
The two e-methane powered ships work as flag ships for green transportation. The decarbonisation project leads to certain investments such as renewable energy capacity for the corridor and vessel retrofitting, but also enables higher value of transportation. As more ships start to utilize locally produced fuels, less fuel imports are needed.

Impact on the Security of Supply (6)
When ships are provided with locally produced fuel, less fuel imports are needed in the countries on both sides of the corridor. Local fuel generation and production leads to better security of supply than is the case when relying solely on imported fuels.

Impact on Export Potential (7)
The interest towards green ships may cause positive reactions among the shipowners, and it is possible that demand for new kinds of green vessels can attract shipowners to order new environmentally friendly ships from the shipyards.

Impact on Jobs (8)
Local energy production, whether the fuel is based on biomass or an electro-fuel, requires employees to build, operate and maintain the facilities. There will also be a likely need for more workforce at shipyards.

Impact on R&D (9)
Starting the operations with a renewable fuel has required a lot of research when considering the needs for new pricing and business models to operate environmentally sound ships. In addition, designing hydrogen, methanol, or ammonia ferries require significant investments in research and development.

Value of transportation (10)
People are ready to pay for sustainable products [9, 10], and it is likely that consumers will be ready to pay more for sustainable transportation as well. The extra value of green transportation shall be collected in the form of ticket and lane metre price.

Cost of Transportation (11)
The costs of environmentally friendly shipping will be distributed to passengers and customers transporting cargo over the seas. Even though the renewable fuel is two to three times as expensive as the fossil fuel, it is to be kept in mind that when the costs of transportation are divided to items transported, the price premiums for products are about one to three percentages higher than for goods transported with fossil fuels [11].

Safety of Transportation (12)
When new kinds of fuels are utilized in shipping, safety of the employees and passengers is one of the most important concerns. In our study, safety issues of the change were considered only on qualitative level.

Impact on Sustainable Tourism (13)
Environmental analysis included a comparison in which taking a cruise was compared to a situation in which a person drives an average diesel car as far away as s/he can with the same amount of emissions the cruise generated.

Impact on Sustainable Manufacturing and Retail (14)
It was estimated that about 6% of the goods transported with ships between Finland and Sweden could be carried by these two environmentally friendly ships, thus providing an opportunity for local manufacturing and retail business to capitalize on carbon-neutral transportation of their products.

Impact on Renewable Energy (15)
The study calculated also that if the ship would start consuming e-methane, renewable energy capacity needed to secure the amount of fuel needed would be large per vessel.

Impact on Land Transportation (16)
The study included also a scenario in which EV recharge stations would be utilized onboard the ship. Based on the estimations, the recharging stations would make it possible for hundreds of EV trucks to utilize the ship when crossing the sea annually.

Impact on Shipbuilding (17)
The choice of decarbonization technology for a maritime corridor can lead to more profound changes. Investments in ships running with renewable fuels is an example.

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Stations of the Future: A Study on EV Charging Stations Considering Users' Requirements and Expectations

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Abstract. One of the products included in *USER-CHI* project is the definition of the charging stations that not only EVs and LEVs require, but also fulfil the needs and expectations of the end users. A qualitative and quantitative user research following the user experience principles have been performed, achieving a deep knowledge of EV drivers' charging preferences and patterns in order to increase their acceptance. As a result of this research, we have identified basic requirements, increasing value and desirable features that are related to the charging process of an EV, that should be included in a charging station aimed to achieve end users' expectations. Taking these features, we have defined four different concepts of stations of the future, namely: *Intermodal Station*, *Highway Station*, *LEV Charger* and *Urban Station*. Concepts are presented in a handbook, following a composition that includes: a colored realistic sketch of the concept, a presentation of its main features organized in three topics (*Technologies-Services-Location*), and business models related to the concept. These business models were generated with the five demo-cities that are part of the *USER-CHI* consortium. The business model related to each concept, is a combination of the seven business models defined with the cities -*Logistics Hubs*, *Citizen e-mobility Station*, *City Centre (Park&Charge)*, *e-Trucks*, *e-Taxi Stops*, *Special Events*, *Mobile Charging Stations*. The most relevant features of the resultant business model related to each conceptual station are presented in a new reduced format, including four topics: *The Value*, *The Business*, *The Market* and *The Flow*.

Keywords: user research · EV · LEV · charging station · business model · USER-CHI project

1 Introduction

As the most energy-consuming sector in Europe [1], and the largest cause of air pollution in cities [2], the transport sector needs to tackle a profound decarbonisation revolution. Disruptive technologies and business models are also deeply transforming the way European citizens understand mobility [3]. Citizens' rising environmental awareness

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and new mobility habits present a unique opportunity for the large-scale implementation of electric vehicles (EVs). European Union (EU) has made a commitment to ensure full coverage of EV infrastructure across its members [4]. However, a dense European interoperable and publicly-accessible charging infrastructure network is far from being a reality. In fact, lack of charging infrastructure, insufficient vehicle autonomy and the long-time required for recharging are considered to be the main drawbacks that differentiate electric vehicles from traditional internal combustion vehicles in regard to the user experience [5, 6].

On the other hand, current business models and revenues generated from charging infrastructure are not sufficient to ensure a sustained and healthy market growth. These results in a lack of confidence in the EV sector as a whole and leads to uncertain users hesitating to buy EVs, triggering a vicious circle of a frozen demand because of an unsatisfactory offer and vice versa.

One of the key elements to break these vicious circles is to design and develop charging solutions focused on solving and satisfying the needs and desires of users from different socioeconomic backgrounds and customer segments. In this context, USER-CHI project [7], a Horizon 2020 project, plans an active collaboration between industry, cities and citizens in order to co-create and demonstrate a set of solutions and tools to foster the massive deployment and market acceptance of electric vehicles in Europe.

One of the products related to project objectives is the definition of a guide, with recommendations on how a charging station should be, in order to fulfil users' requirements and expectations. When charging an EV, users are demanding a procedure for booking a charging point that ensures its availability at the time driver arrives [8]. But this must be requirement, based on the availability of a dense charging point network, is only the first step for user satisfaction. The following step is features that facilitate the charging process like standardization, interoperability or automatic user detection, and the desirable requirements are those which allow to control as much as possible the charging process, like real time monitoring or different fees programs.

In order to define facilities that cover these requirements, technology plays a major role, but another factors, like urban planning or intermodal mobility should be also taken into consideration, as electromobility must cover not only the long-range trips, but also urban and periurban transport.

This paper presents the results obtained in the process of defining the charging stations that the users' requirements and electromobility demand.

2 The Stations of the Future Definition

2.1 The Co-creation Process

User requirements' collection generated in the qualitative and quantitative research [8], were employed as entry data of a co-creation process, participated by all the USER-CHI consortium partners, including technology developers, research institutions, business consultants and city councils. The first session of the co-creation process, generated two concept solutions: one for an intermodal station and another one for a LEV station. Both concepts were converted in digital sketches, and Fig. 1 shows the one presenting the intermodal station.

A second online session to assess these sketches were appointed. As a result of this assessment, we got that intermodal station concept was not adequate for a city centre, where the space is scarce, and consequently expensive. Moreover, the concept did not include facilities for logistics operations, and an intermodal ticketing point. On the other hand, we also collected some improvements for the LEV charging station, as the need of modularity for the solution, the attractiveness of the design, or to include battery swapping solutions.

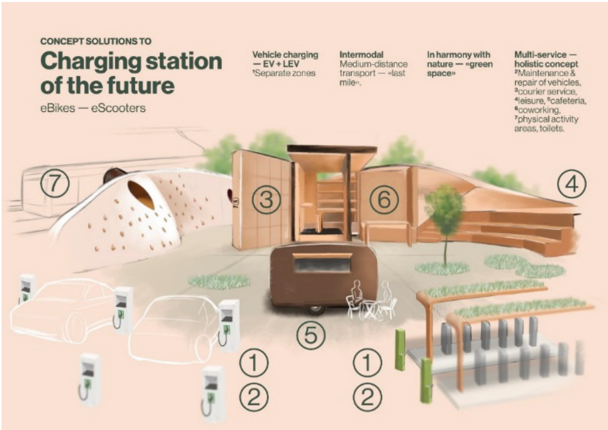

Fig. 1. Digital sketch of the first concept design generated. (Source: Image courtesy of USER-CHI project, reproduced with permission)

Table 1 Presents the main features of the four final concepts that we finally defined, organized in three categories. *Technologies* refers to the main technological solutions to be included in the facilities, *Services / Users demands* refers to the services that end users are expecting to find, in order to cover their main demands, and *Location* refers to places that are likely to host a station, with the described characteristics.

2.2 The Business Models' Definition

The scope of USER-CHI project included the analysis and definition of business models [9], considering different environmental scenarios and a multi-stakeholder approach, specifying for each demo city partner of the project, which is interested in the BM: the market characteristics, market trends, market limits and constraints, target clients and their profile, market size and business opportunities to make them viable, attractive, and economically sustainable. As a result of this process, seven business models were defined, namely, *Logistics Hubs*, *Citizens e-mobility stations*, *City Centre (park & charge)*, *E-trucks*, *E-taxi stops*, *Special events* and *Mobile Charging Stations*.

The conceptual stations presented in Table 1 are not represented completely by none of the business models defined, but a combination of them does. Then, and following this matching process, we got that:

Table 1. Main features of the concept stations classified per categories.

		Technologies	Services / User demands	Location
Intermodal Station	Electric cars – eBikes – eScooters – Public transport	→ Chargers for LEVs → Shared electric scooters (eScooters), electric-assist bicycles (eBikes) and electric mopeds → Slow chargers (AC, Inductive charging) → Fast chargers (DC) → Pay for charging (not parking), interchangeable payment method → Rental and shared vehicle area	→ Standard and fast chargers → Inductive charging for EVs + Maintenance + Parking lot → Chargers for LEVs → Intermodal ticketing point → Cafeteria → Toilets → Lockers & Courier service → Coworking & resting area	→ Nature integrated → Anti-theft / safe zona → Railway station, city accesses, university campuses → Big space is required
Urban Station	Electric cars – eBikes – eScooters - Electric vans	→ Slow chargers (AC) → Fast chargers (DC) → Parking & Charging booking → Restricted access → Interchangeable payment method	→ Parking & Charging service for LEVs and EVs → Lockers & Courier service → Logistics → Short stays → Loading/Unloading area	→ City Centre → Neighbourhood → Shopping area
Highway Station	Electric cars – Electric vans	→ Fast chargers (DC) → Charging booking	→ Interchangeable payment method → Cafeteria → Toilets → Coworking & resting area → Vehicle maintenance → Playground / Physical activity	→ Highway

(*continued*)

Table 1. (*continued*)

		Technologies	Services / User demands	Location
LEV Station	eBikes – eSccoters – eMopeds	→ Photovoltaic panels connected to grid → Modularity → Battery storage cabinets / Battery swapping → AC chargers → Charging booking	→ Secure parking → Vertical parking → Interchangeable payment method	→ Chargers in urban furniture, street lights and benches → Bus canopies, underground → University campus

- *Intermodal Station* is a *Logistics Hubs-Citizen e-Mobility Station-City Centre (Park&Charge)-e-Taxi Stops*,
- *Urban Station* is *Logistics Hubs-City Centre (Park&Charge)-e-Taxi Stops*,
- *Highway Station* is *Citizen e-Mobility Station-e-Trucks-Special Events-Mobile Charging Stations*, and
- *LEV Station* is *Citizen e-Mobility Station-City Centre (Park&Charge).*

The main features of the business models related to each conceptual station were melted employing the well-known CANVAS business model developed by Osterwalder [10]. The most relevant features of the business model related to each conceptual station were presented in a new reduced format, including four categories: *The Business* bringing together the boxes of panel's left side (*Key Partners-Key Activities-Key Resources*, *The Market* bringing together the right side (*Customer Segments-Customer Relationship-Channels*), *The flow* bringing together the lower boxes (*Revenue Streams-Costs Structure*), and *The Value.*

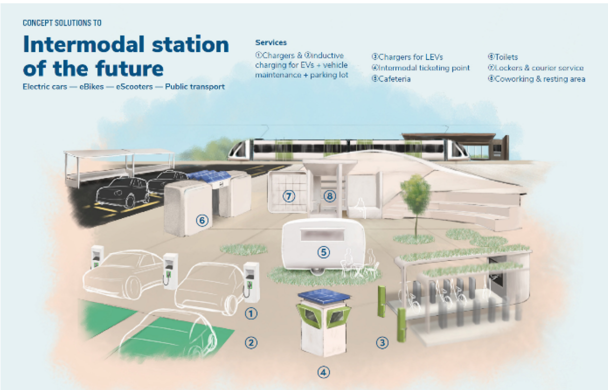

Fig. 2. The Intermodal station of the future. (Source: Image courtesy of USER-CHI project, reproduced with permission)

3 Results

Concepts designs presented in the format of digital sketches have been created to introduce the main features of the four defined stations (Table 1). Figure 2 presents a station focused on facilitating multimodal mobility, hosting communal and individual transport solutions in the same facility.

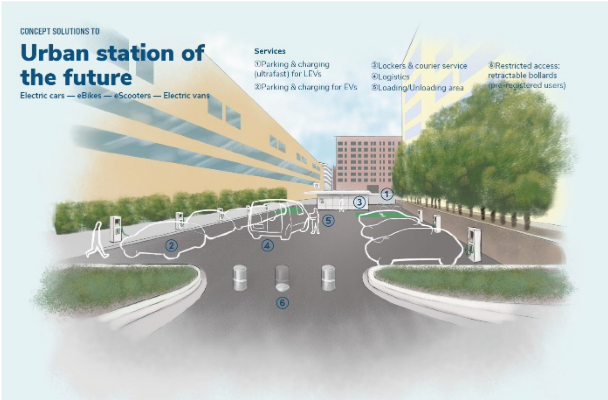

Fig. 3. The Urban station of the future. (Source: Image courtesy of USER-CHI project, reproduced with permission)

Different charging technologies for EVs and LEVs are included, as part of the increasing value services that users are expecting. In addition, the concept also includes services that are more related with the desirable features demanded by the users, such as resting area or coworking facilities. On the other hand, the concept also considers the needs of the city logistics.

Figure 3 presents a concept charging station to be located in the city centre area, minimizing the impact in an area expected to be saturated. The concept proposes a charging solution focused on parking&charging, where the accessing control is required. As in the case of the intermodal station, logistics are included in the solution.

The sketch of the *Highway station of the future* (Fig. 4) presents a facility that is not far from the stations we have today in the European highways, but the concept goes deeper in the additional services that users are going to employ while charging an EV in a long-range trip. Fast chargers are a must in this station, but the concept aims to cover additional needs, as charging solutions for e-trucks, or mobile charging stations to assist drivers with problems caused by EV's autonomy or extreme weather events (Fig. 4).

LEV chargers of the future is a multimodal station for city areas, where light electric vehicles are combined with the public transport, to promote active mobility and intermodal transport. The presented concept aims to have a low impact in the city, adapting to the urban furniture and employing sustainable charging technologies as those based on photovoltaic panels.

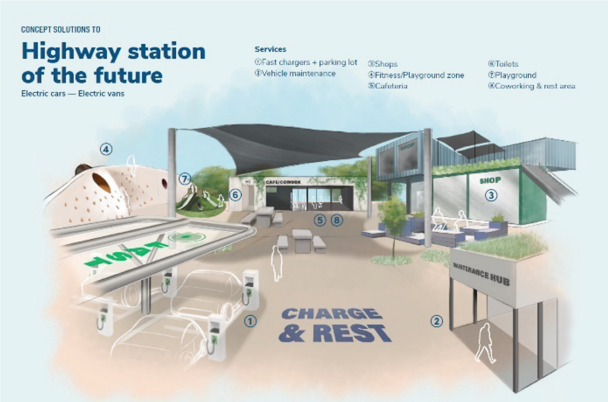

Fig. 4. The Highway station of the future. (Source: Image courtesy of USER-CHI project, reproduced with permission)

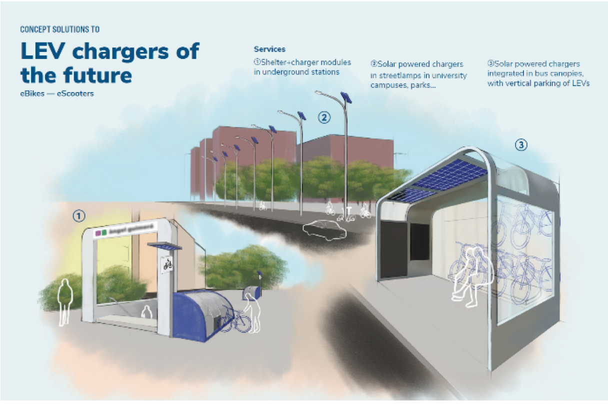

Fig. 5. The LEV chargers of the future. (Source: Image courtesy of USER-CHI project, reproduced with permission)

4 Conclusions

The paper presents four concepts of charging stations for EVs and LEVs, intended to cover not only users' increasing value requirements, but also desirable requirements. The sketches are aimed to present feasible solutions, but are not intended to define standards or closed solutions; in fact, the authors' objective is to point out the need of generating new charging infrastructures for the new electromobility.

The authors want to thank all the *USER-CHI* consortium members for their active participation in the generation of the results presented in this paper (available on project website [11]), especially to the project coordinator, *ETRA I+D*. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No [875187].

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Activity-Based Travel Demand Model: Unveiling the Dynamics of Modern Travel Behavior in Dublin

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Abstract. As the Dublin is moving forward towards a brighter future on the bases of three main pillars: reducing car dependency, improving the public transport, and most importantly achieving those goals in sustainable environmentally friendly approaches, it implies that major changes to current existing travel behavior are on the way. Moreover, it is always healthy to remember that not only the proposal of many projects is vital but the ability to coordinate their planning, evaluate their potential impacts, assess their actual influence, and utilize the available feedback loops to ensure the most appropriate results the public seeks. Given the serious deficiencies that conventional four-step travel demand modeling approach, therefore, it is the time to invest towards developing a new tool that can facilitate the transformation that Dublin and Ireland are looking after with a development of an activity-based travel demand model that has the potential to be the suitable candidate for answering 'what if' answers.

Keywords: Travel demand modeling · Activity-based travel demand modeling · Transport policy

1 Introduction

A transportation system, including its infrastructure, level of service and maintenance, as well as the social and environmental benefits it provides, have been identified as one of the primary variables that dictate the economic prospect of interested places (such as cities, regional areas, and countries). Other key aspects include social benefits and environmental advantages) [1]. These, combined with an extensive list of additional causes, underline that the transportation system is a vital part of a thriving contemporary society and economy. Therefore, for the sake of our communities' social and economic well-being as well as the future efficacy of the transportation system, it is imperative that we foresee both the possibilities and the challenges associated with system performance [2]. This suggests that a robust and secure transport system is essential to a country's economic health and community quality of life, and Ireland is no exception. Transportation networks' capacity to offer mobility and accessibility may shape how land is

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utilized, which in turn can have a long-term impact on human habitation. The global transportation spending is estimated by Lefevre et al. (2014) to be between US$1.4 and US$2.1 trillion annually [3]. It is anticipated that the annual investment will continue rising on a steadier basis as a result of the increased connectivity between cities and regions. The ever-increasing population of urban areas has introduced an element of ambiguity into the potential future paths of urbanization. This, in turn, impacts the spatial and functional layout of transportation systems and the circulation of capital funds associated with transportation. Therefore, decisions must be made in order to mitigate any potential dangers that may be inherent due to the ambiguity. The investment in transportation is particularly significant, and decisions concerning transportation systems are crucial since highways, trains, and stations determine long-term trends in urban expansion and last for generations. It is of the utmost importance that prior to bringing plans and programs into action, the necessary expenditures be adequately justified, the necessary permissions be obtained, and the necessary social and environmental consequences be thoroughly assessed. The principal objective of transportation planning is to offer information and data to facilitate decision-making for transportation systems so that services and facilities are developed at a competitive price with the least possible negative impact on the environment and promote economic activity.

2 Travel Behavior in Dublin

The central role of Dublin as the capital and as the primary financial hub of the nation has been the case for many years and continues to carry on to this date. According to the latest census data in 2022, Dublin is home to over 28.3% of Ireland's population and employs about 30% of the labor force (see Fig. 1). Despite the vital role that Dublin serves in the nation's economic prosperity as acting as an attraction center for job seekers, the economic boom has not been accompanied by an equitable expansion of transport; therefore, the modal share of the private transport modes (i.e., car driver or passenger) has managed to be dominant over the years (see Fig. 2). Yet, numerous other areas of interest are directly influenced by this substantial dependency on cars. The expense of congestion and the implied environmental effects that are induced are the two main ones. First, the cost of traffic congestion. Based on a 2017 Department of Transport study, the time costs of traffic congestion could increase by more than 75% by 2025 and more than triple by 2033, peaking at 2.08 billion in the Greater Dublin Area alone [4].

Regarding the effects on the environment, public awareness has increased notably throughout the years, which has been an important driver together with others that contributed to the push towards the issuing of a series of Climate Action Plans (CAP) where the most recent has just been published in March 2023, which is entitled: 'Changing Ireland for the Better.' The CAP23 Transport Section sets high standards for the transportation industry, requiring a 50% reduction in emissions by 2030 and complete decarbonization by 2050 [5]. Many interventions at six main domains are proposed to enable the ambitious CAP 2023 targets to be achievable. These domains include, but are not limited to, decreasing the cost of public transportation and elevating its infrastructure through significant projects and services. These projects and the increased number of micro-mobility businesses in Dublin—from bike sharing like DublinBikers and Bleeper

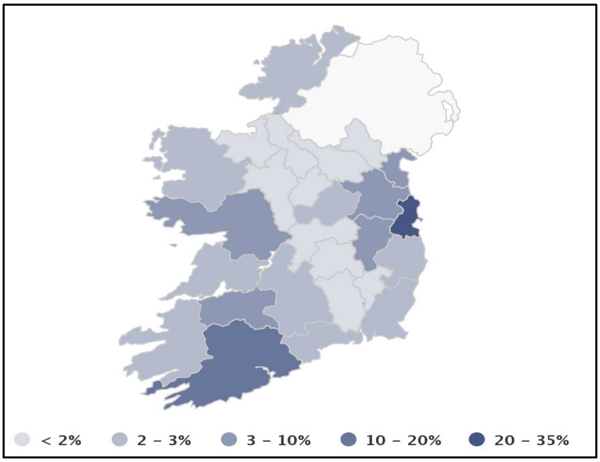

Fig. 1. Percentage of persons at work by county 2020. Source: Central Statistics Office, County Incomes and Regional GDP 2020

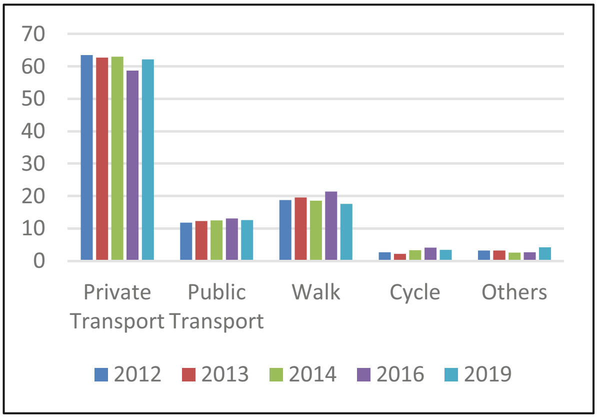

Fig. 2. Percentage distribution of journeys by mode of travel for Dublin, between 2012 to 2019. Source: Central Statistics Office, National Household Travel Survey

to shared e-bikes for delivery run by MOBY Bikes—as well as e-scooters are poised to join the other modes of transportation as soon as they receive the necessary regulations. All things considered, it is clear that Dublin is making every effort to eradicate the era of reliance on cars, which suggests certain changes in the way Dubliners travel behavior.

3 Approaches to Travel Demand Modeling

Traffic counts were carried out to evaluate the utilization of transportation networks before the 1950s. Either the current travel demand or coarse-grained, uniform growth factor projections based on historical trends were used as the basis for demand modeling.

More advanced prediction tools were needed for the rapid highway development in the 1950s so that future travel demand could be satisfied and the economic effects could be evaluated. This era saw the advancement of computers, which made it possible to put large-scale travel demand models into practice. This decade saw the emergence of a strategy that was codified in the 1960s and is commonly known as the four-step travel demand model. The four-step models use a sequential process to anticipate traffic flows and travel demand. Adoption of the four-step approach gained popularity by the end of the 1960s. Though there was a trend toward inventory-based planning in the 1970s (e.g., low capital options, dynamic, policy-sensitive, and demand-responsive systems), modern planners believe that a number of problems and arguments have arisen that have hampered the application of the four-step method [6]. The original four-step technique had undergone significant modification during the 1970s and 1990s in response to growing criticism. Nonetheless, the enhanced four-step procedures remain essentially aggregate. Furthermore, in the 1980s, the majority of planning agencies continued to rely heavily on the aggregate four-step process, with the disaggregate techniques having only been evaluated in a small number of instances. Planning frameworks and accessible demand modeling techniques diverged more in the 1990s than they had previously because capital-intensive expenditure was no longer the primary emphasis of transportation planning in developed regions; instead, travel demand and transportation system management and policy took center stage. Consequently, the use of disaggregate models and simulations became more prevalent, which prompted the creation of activity-based travel demand models as viable substitutes for the four-step process. The idea that the desire for travel arises from the urge to participate in activities is the foundation for modeling travel demand from an activity-based approach. Several types of activity-based models have evolved in the literature to include the underlying premise from diverse perspectives. These models adhere to the same principles. The development and evaluation of activity-based travel demand models have received support from numerous cities and regions in North America (primarily the United States), Europe, and Japan over the past 20 years. Research into activity-based models is still ongoing in order to incorporate new theoretical developments and planning scenarios.

4 Current NTA Model' Challenges

4.1 Overview of the NTA Regional Modelling System

As the core of its mandate, the NTA employs transport modeling to inform the decisions needed during strategy creation and to evaluate schemes and policy initiatives. Thus, the National Transport Authority (NTA) developed the Regional Modelling System (RMS) to help with the comprehensive evaluation of transport initiatives and plans throughout Ireland, especially in the country's five largest cities: Dublin, Cork, Galway, Limerick, and Waterford (Fig. 3).

4.2 Challenges of the NTA Regional Modelling System

Despite the NTA's many updates and enhancements, such as the ability to account for simple and complex tours, extensive demand segmentation, and the incorporation of five

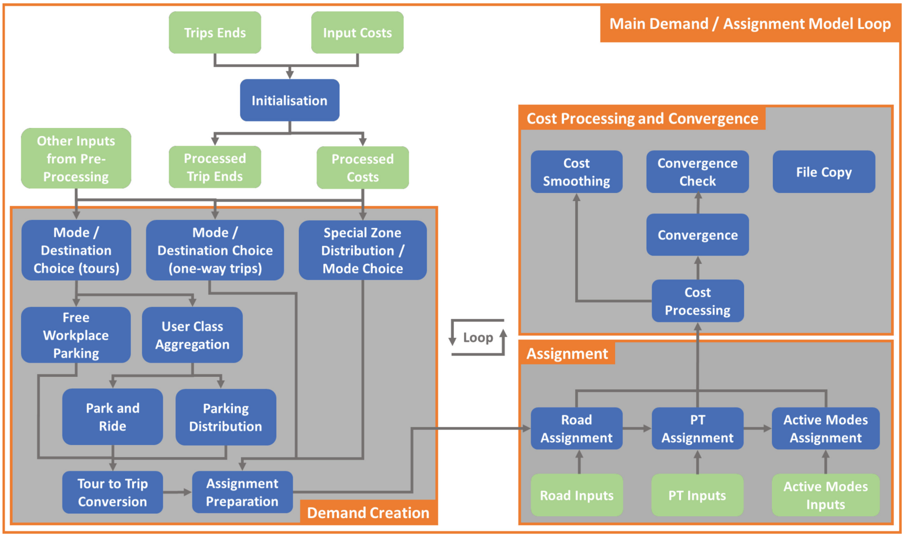

Fig. 3. The Main Demand (Assignment Model Loop) of the Regional Modelling System Structure. Source: Model Development Report, East Region Model, Model Version 3

different modes of transportation, the regional model still faces a number of obstacles. These obstacles fall into two main categories: modeling approach limitations and changes in travelers' habits. The fundamental component of regional modeling is the four-step travel demand modeling (FSTDM), which has been criticized extensively and subjected to multiple limitations by a variety of literature sources (see, for example, [7]). The aggregation behavior is one of the most significant disadvantages of FSTDM since these models only capture the average behavior of a population, making it difficult to fairly reflect the possible effects of contemporary transportation models (like the e-scooter) and policies (like the shared economy). The omission of a key aspect of the nature of the transport being "derived demand" [7] is another essential component that is missing.

5 Recommendations

The use of activity-based travel demand models (ABTDM) can help to apply the behavioral concepts that form the foundation of established microeconomic and social science theories more widely into the transportation planning context more efficiently.

Compared to traditional models, these models enable the consideration of richer and more data, such as segmenting the time of day into far finer temporal units [8]. Additionally, two recommendations are made to boost ABTDM acceptance, which is currently low [9]. It is imperative to establish a ranking system for the existing ABTDM to provide practitioners with comprehensive insight into the various ABTDM's performance across many domains. Second, in order to foster the implementation of ABTDM, it would be important to propose a uniform and simplified modeling method.

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Europe's Rail FP4- Rail4EARTH Sustainable Rail Systems Progress Point of the European R&D Program

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Abstract. The scope of the European R&D railways project FP4-Rail4Earth (95M€ budget, 4 years, started in December 2022) funded by the European Commission covers the sustainable rail system including rolling stock, infrastructure, stations, and their sub-systems.

The objective is to improve the existing sustainability performances of railways, to reinforce a more attractive and resilient transport mode and to contribute towards the objectives of a Climate Neutral Europe for 2050.

The decarbonisation of diesel trains, the noise and vibration reduction, the energy saving, circular economy, resource consumption, resilience to climate change, attractiveness of passenger trains are at the heart of the project. 38 technology demonstrations are foreseen in the project and the present article is presenting the most important or advanced ones.

In total 71 European partners, including all major European railways operators, infrastructure managers, European railways industrials and research centres are:

- Identifying the needs of operators including the European sustainable transport policies, such as the smart and sustainable mobility strategy,
- Developing and demonstrate (up to TRL7) the new technical solutions, increasing the environmental performance of the railway system.

In parallel with the technical Key Performance Indicators quantification (Energy, CO2, noise, etc.), the Life Cycle Cost of the new solutions are quantified, verifying that they have viable economic models ensuring a rapid commercialisation after the end of the project in 2026.

The FP4-Rail4Earth project, global scope and objectives are presented here at TRA2024 as well as the intermediate results after 16 months of project progress.

Keywords: railway · Sustainable transport · circular economy · CO2 · energy efficiency · battery and hydrogen trains

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1 Introduction

Note: this paper was written in September 2023 and updated in December 2023. The presentation done in TRA2024 will be updated with the latest March 2024 news and progress on the project.

2 Objectives and Progress

2.1 Sub-Project 1 – Low Carbon Solutions for Rolling Stocks

This first sub-project of FP4-Rail4EARTH is dedicated to low carbon trains, mainly to supress Diesel traction on unelectrified lines. Since a while, the first hydrogen hybrid regional trains, battery or hydrogen hybrid shunting locomotives have been sold in Europe, but the real take off to replace all Diesel-powered trains is still needing additional technical performances improvements and/or life cycle cost reduction.

This sub-project deals with energy, CO2, LCC, noise reduction (compared to Diesel traction) and increased regional trains autonomy (compared to existing - mid 2023 - battery trains).

Several normative debates take also place in this sub-project like fast charging, external energy supply interfaces between the Battery Electrical Multi Units (BEMUs) and the infrastructure.

The project partners gather needs from some of the major railway operators and train manufacturers to progress on the definition of the European railway requirements for low carbon propulsion systems to enhance more standardised and so more cost-efficient solutions.

One of the main challenges is to increase the BEMU autonomy up to 200 km to cover 90% of the daily circulation needs of European operators. To achieve this goal, several levers are needed: minimise the train energy consumption via train weight reduction, train aerodynamic improvements, trains consumers better efficiency (like the air conditioning system), also increase the energy storage embarked on board via a drastic improvement on the energy density of the Energy Storage System.

The demos planned as outcomes are:

- High performances battery powered regional trains, TRL6–7 in 2026,
- Hydrogen hybrid locomotive TRL5–6 in 2026,
- Hydrogen power plant for inspection vehicle TRL5 in 2026.

Progress and results achieved in 2023 are:

- The requirements for the next generation European BEMU are finalised (Energy Storage System, external power supply, traction chain…) allowing the start of design phase,
- The technology of the cells is chosen, and the first cell tests has started,
- A complete system modelling including infrastructure installation configuration was detailed to guarantee the battery performance over a line,
- The assembly and mounting of Energy Storage System on the future demonstration train is at stage of general studies, analysing volumes and weights for the new components in refurbished trains, some drawings to fit are done,

- Systems to improve efficiency of H2 power plant identified.,
- Refuelling interfaces for H2 based on land-vehicle interface.

2.2 SP2 – Low Carbon Solutions for Infrastructures and Stations (Laurent)

This FP4-Rail4EARTH sub-project 2 is dedicated to the railway's infrastructure, both the classical ones supplied by electricity and the new ones for hydrogen distribution to the railway vehicles.

It deals with energy, CO2, and LCC reduction compared to existing infrastructure.

We present at this stage only the work done on the smart infrastructure power supply.

The objective is to realise before end of 2026 a demonstration of 25 kV parallel substations to reduce the need of infrastructure reinforcement and suppress voltage neutral zones. Different strategies are developed also to store energy on the ground of these AC infrastructures.

Different benefits are expected by operators: Improve the energy consumption of the lines, exploit the train braking energy locally, make facilities management more flexible. Infrastructure managers are expecting new solutions to improve the infrastructure technical (power supply quality, network unbalance) and environmental (energy and CO2 reduction) performances. The engineering teams will have new design/optimisation tools for AC and DC network.

Progress and results achieved in 2023 are:

- Requirements of Railway Interline Power Flow Converter for double side feeding of 50 Hz AC traction substations,
- Converter topologies compared to allow multiple ESS access to the railway traction system and development of new control strategy to integrate ESS,
- Requirements for the AC grid reviewed, and DC design/sizing tool validated.

2.3 SP3 – Sustainability and Resilience of the Rail System

This third sub-project of FP4-Rail4EARTH is a working area on holistic topics transversal to the other sub-projects aiming to:

- The pre-standardisation of battery interfaces, and the development of smart energy management (WP1),
- The adaptation to climate change (WP2),
- The mitigation of noise and vibrations (WP3),
- The development of circular economy & environmental data management tools and solutions (WP4).

WP1: The replacement of Diesel train with efficient alternative energy trains implies technological solutions at train, operational and infrastructures levels. The goals are to pre-standardise:

- The interfaces between battery and train to reduce maintenance costs for maintainers and facilitate performance's upgrading with new technologies,
- The communications protocol between battery trains and operation to optimise the use of the train's fleets, the reliability of transportation plan and the energy savings,

- The interfaces between train and infrastructure to optimise the sizing of substations and provide new energy services by controlling the charge/discharge.

Progress and results achieved in 2023 are[1]:

- A state of the art of technological solutions for charging of battery trains and hydrogen fuel trains and list of parameters to exchange between traction system and train driver desk as well as traffic management system,
- Simulations done with various partial electrification scenarios to evaluate the performances of alternative drive trains and lifetime of energy storage system.

WP2: The aim is to implement the EU adaptation to climate change strategy to the railway sector to make it resilient to climate. The work will focus on:

- A smarter adaptation to the climate change to allow reliable decisions on adaptation investments for existing and future assets,
- A faster adaptation by identifying existing solutions.

Progress and results achieved in 2023 are[2]:

- State of the art of adaptation to the climate change standards and regulations; climate change prediction tools; weather conditions impacting railway assets and operations; sensitive assets; risks; and technical existing solutions,
- Datathon made by the French operator to show the feasibility of a correlation between meteorological data, rolling stock's maintenance data and train's operation data.

WP3: The growth of railway modal share is known as the most efficient solution to mitigate the effect of transportation on climate change. Even if the noise and vibrations effects on the population are proportionally lower compared to other modes, it necessary to continue to limit them. After years of constant progresses in decreasing noise levels around railway infrastructures (rolling stock design, noise barriers, dwelling insulation), further global level reductions are becoming increasingly costly. It is therefore utterly important for railway operators, infrastructure managers and rolling stock manufacturers to better understand which aspects of noise emissions impact neighbours the most, to better target noise abatement measures and develop effective design and maintenance mitigation measures efficient over life span.

Progress and results achieved in 2023 are[3]:

- A pilot study carried out on annoyance responses gathered at residents' homes close to high-speed lines in France, and then methodologies defined, both for studying high-train annoyance and tonalities in order to develop a new noise perception indicator,

[1] This paper will be presented at TRA2024: "From Shift2Rail to Europe's Rail, future perspectives for alternative drive trains standardizations and energy efficiency".

[2] This paper will be presented at TRA2024: "Railway assets resilience to climate change - Application of the smarter and faster adaptation EU strategy".

[3] This paper will be presented at TRA2024: "Assessing the perceived annoyance of high-speed trains with an experience sampling method".

- A catalogue of ground-borne vibration mitigation measures,
- Development of calculation model and prediction tool of ground-borne vibrations.

WP4: the objectives are to develop sector methodologies and tools for the efficient implementation of circular economy and eco-design solutions in the railway sector. Two main topics are addressed:

- Development of environmental data management tools and pre-standardisation of environmental indicators,
- Development of circular economy solutions as a marketplace facilitating the reuse of material from train to infrastructure.

Results achieved in 2023 for both topics are a state of art of existing rules and solutions in other sectors and the development of shared requirements.

2.4 SP4 – Sustainable Electromechanical Components for Rolling Stocks

The sub-project 4 targets the improvement of electro-mechanical components and subsystems for the rolling stock, in order to reduce energy consumption, CO2 emissions, weight and noise and increase indirectly the train's autonomy (in case of battery trains) and its resilience to climate changes. The sub-project contains several demonstrations:

- Developing and introduce to the market electro-mechanical braking system while targeting energy savings on the involved subsystems and reduce associated maintenance costs by reaching TRL6 for 2025 and prepare for later evolutions,
- Introducing optimised (energy, weight) motors and gearboxes, and high-performance bogies following circular economy principles and reaching TRL6 in 2025, using new concepts and new materials for bogie design,
- Delivering alternative technologies to replace hydrofluorocarbon refrigerants of the Heating, Ventilation and Air-Conditioning (HVAC) system using new refrigerants or new cooling technologies targeting TRL6 in 2025.

Progress and results achieved in 2023 are:

- Technological scouting, concept definition and design,
- Collegial work for interoperability standards adaptation,
- Comparability criteria (KPIs) for technological assessment determined,
- Two air-less actuator types are tested at static and dynamic test bench.

2.5 SP5 – Healthier and Safer Rail System

The fifth sub-project of FP4-Rail4EARTH is dedicated to the development of solutions for air quality and non-contaminating materials guaranteeing to the railway passengers a healthy and safe journey, and therefore to the rail transport its resilience to eventual future pandemics. Many suppliers have proposed materials offering new functionalities claiming to be bactericidal, germicidal, fungicidal or even viricidal. However, the efficiencies are not verifiable directly because standards and testing protocols used are not adapted to rolling stock applications or operating constraints.

The goals are to develop testing protocols helping to develop, test and assert technically and economically the efficiency of healthy solutions for rolling stock (WP21–22) and covered stations (WP23) considering the technical installations, the effects on thermal comfort and the air quality needs. Complementarily, alternative ventilation concepts and air purification systems are developed based on computational fluid dynamics (CFD) tool chains and selected experiments (WP21) and their applicability will be demonstrated in realistic train geometries (WP22). For covered stations and tunnels, air-quality assessments will be conducted in different locations throughout Europe and different sensor systems will be evaluated.

Progress and results achieved in 2023 are[4]:

- An evaluation of different ventilation concepts for rolling stocks with regard to aerosol spreading from a local source based on tests and simulations,
- An assessment of existing solutions in regard of air distribution and disinfection technologies for rolling stock implementation addressing relevant pollutants as PM, VOC, bacteria, virus and fungi,
- A survey of the existing standards on air quality improvement was done in parallel with the determination of the best evaluation criteria for novel air purification technology selection which might be installed into the HVAC unit,
- The development of measurement protocols with 3 levels of validation (component, laboratory, train) for 3 domains of activity (air quality measurement, air treatment and surface treatment). A proposal of solution to measure air quality on board and display these results in a dashboard including an air quality index,
- The definition of measurement methods to monitor particulate pollution in underground railway stations and asses the efficiency of air treatment systems: long-term, punctual, experiments to measure the efficiency of the air treatment devices,
- An evaluation of low-cost sensors, field test measurements in covered stations and development of Artificial Intelligence based tools to predict air quality.

2.6 SP6 – Sustainable and Modular Interiors for Rolling Stock Attractiveness

The sixth sub-project of FP4-Rail4EARTH is dedicated to build the key factors to design sustainable interiors focused on modularity of interiors and circularity of their materials, and propose new interiors based on the defined KPIs with a demonstration based on virtual and physical mock-ups. The objective is to allow a cost efficient, sustainable and quick adaptation of the interiors architecture and materials fitting the evolving market needs all along the lifetime of the rolling stocks.

Progress and results achieved in 2023 are[5]:

- State of the art of modularity, introducing the notions of modularity in production, modularity in design, and modularity of use. The modularity in design is the one agreed among the partners for this sub-area,

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[4] This paper will be presented at TRA2024: "Influence of the airflow concept on the aerosol spreading in a generic train compartment".

[5] This paper will be presented at TRA2024: "New attractiveness of rolling stock: circular and modular interiors".

- Six issues against the generalisation of modularity for interiors were evaluated: design of new parts - no carry over, adjustments and reworks needed, validation process, complex supply chain, perceived quality and customization, short obsolescence time of new technology. Opportunities and challenges for modularity were found: the challenge of time to market, the challenge of the design for second life, the challenge of the carry over, the challenge of the validation process, the challenge of forgetting the tailored design and the challenge of the just viable technology,
- Six issues were found also for circularity: railway's design not adapted, market not ready for railway, validation process, complex supply chain, perceived quality and customization, short obsolescence time of new technologies or functions,
- A preliminary literature study on the possibilities of biomimicry for circular and modular train interiors revealed the biomimicry potential.

3 Conclusion

After the 16 first months of this 4 years project, many progress have been done in the wide scope of the projects, both on future hardware technologies and software new solutions. New design approaches like circular economy, resilience to climate change applied to rolling stock, infrastructure are described. The work progress is quantified once a year on the project Key Performance Indicators (energy, CO2, noise, autonomy of BEMU trains, Life Cycle Cost of the new solutions).

A Review of Policies for Decarbonising Heavy Goods Vehicles in Ireland

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Abstract. The transport sector in Ireland is in need of decarbonisation if the country is to meet its climate targets. Transport is an integral aspect of the nation's economy, with the importation of goods from neighbouring countries of France and the United Kingdom occurring using heavy goods vehicles (HGVs). With the current development in transport decarbonisation and evolution of the energy sector in the country, the adoption of electric vehicles (EV), both battery & hydrogen in the transport sector, may be an attainable pathway to mitigating carbon emissions, especially from the country's heavy-duty vehicles. This review investigates the existing policies as they relate to the Irish transport sector and its decarbonisation targets. It investigates the challenges and the quick points that must be addressed for the decarbonisation targets to be met. It focuses on hydrogen-based transport and the necessary policies that could be explored as pathways to decarbonise the sector, especially the HGVs sector. The study will give policymakers an understanding of immediate actions to take and how these would impact the long-term decarbonisation strategy of the country.

Keywords: Transport Decarbonisation · Irish Transport Sector · Heavy Goods Vehicles (HGVs)

1 Introduction

The decarbonisation of HGVs has become a critical agenda worldwide due to the urgent need to address climate change and achieve sustainability goals [1], as they are a significant source of greenhouse gas emissions. In Ireland, HGVs are defined as vehicles weighing over 3.5 tonnes [2], and their reliance on diesel fuel resulted in 16% of total emissions in 2019, with the transportation sector being a major contributor to the EU's energy consumption and greenhouse gas emissions in 2018 [3]. Figure 1 illustrates that over the 19-year span from 2000 to 2018, the final energy consumption in the transportation sector in the EU grew by 10.8%, while transportation-related emissions increased by 7.0%.

Ireland, like many other countries, has recognised the urgency of decarbonising HGVs and has taken steps to address this issue [4]. In recent years, Ireland has implemented several policies and including providing financial incentives, such as grants and tax relief, to encourage the adoption of low-emission vehicles.

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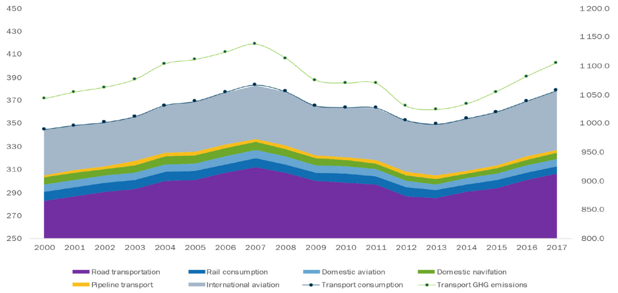

Fig. 1. FEC and GHG emissions in the transport sector in the EU, 2000–2018, Source: S. Tsemekidi Tzeiranaki et al., 2023 [3]

2 Overview of Ireland's HGV Fleet and Its Contribution to Emissions

In Ireland HGVs play a significant role in the transportation sector and contribute to emissions of greenhouse gases [5]. To understand the current state of HGVs in Ireland, it is important to review various sources and studies that provide insights into the haulage industry, adoption of zero-emission vehicles, and relevant strategies.

10-Year Haulage Strategy: The Government's Road Haulage Strategy 2022–2031, launched in December 2022, aims to cut transport emissions by 50% by 2030 in the challenging road haulage industry through measures like route optimisation and alternative fuel adoption. Given the heavy reliance on diesel in the sector, the strategy addresses the dual challenge of expanding operations while curbing emissions effectively [6].

Ireland's Hydrogen Strategy: The National Hydrogen Strategy is an important policy document for Ireland, signalling progress in establishing a sustainable hydrogen sector in line with the nation's net-zero emissions goal by 2050. It emphasises renewable hydrogen as a feasible alternative to fossil fuels in sectors where electrification may not be practical, aiding in emissions reduction. The strategy lays out a roadmap for developing essential hydrogen infrastructure, such as pipelines and storage facilities, highlighting Ireland's commitment to advancing its green hydrogen sector and cutting carbon emissions [7-9].

Zero Emission Vehicles, SEAI, EPA, and SIMI Data: By analysing data from SEAI, EPA, and SIMI, valuable insights can be obtained regarding zero-emission vehicles in Ireland's HGV sector, including registered numbers, infrastructure development, emission targets, and policy initiative [5, 10, 11]. These data sources provide a comprehensive overview of the current status of HGVs in Ireland, their emissions impact, and progress towards zero-emission vehicle adoption, aiding in identifying areas for decarbonisation efforts within the sector [5]. Reviewing this information helps pinpoint opportunities and areas for improvement in advancing sustainable practices within Ireland's HGV industry [10].

Hydrogen Bus Trial 2020: Hydrogen Mobility Ireland (HMI) and DCU conducted research on the performance of hydrogen fuel cell electric buses, showcasing promising results with an impressive 3086 km distance covered over 8 weeks, minimal hydrogen consumption, and zero tailpipe emissions. The trial, backed by various stakeholders, revealed high public satisfaction, showcasing the bus's adaptability across urban, suburban, and rural routes, including challenging winter conditions [12]. The study underscored the efficiency of hydrogen buses with fast refuelling times and highlighted their potential as low-emission options in Ireland's public transport network, aligning with sustainable transport solutions [13].

3 Challenges and Barriers Specific to Decarbonising HGVs in Ireland

Several challenges and barriers specific to decarbonising HGVs exist in Ireland including limited availability of zero-emission HGV models suitable for long-haul transportation [14]. Inadequate charging infrastructure and concerns about the range and charging time of electric HGVs also pose barriers to adoption [15]. In a recent study by Tölke and McKinnon, 811 road freight carriers across 32 European countries were surveyed. The findings indicated that while approximately two-thirds of these carriers prioritise freight decarbonisation, a significant portion, 70%, lack the knowledge needed to implement carbon-reduction measures, and 43% face difficulties in calculating and reporting emissions from their road freight operations [16]. Table 1 below gives a snapshot of the various categories of challenges in HGV decarbonisation.

Table 1. Decarbonisation barriers identified among European transport operators.

Barrier Category	Barriers
Political	Politicians and policymakers are pinning their hopes on zero emissions truck technology to deliver this decarbonisation
Economic	Cost pressures among the majority of small operators
Social	Involvement and buy-in from SME carriers
Technological	Supply of new vehicle technology
Legal	The majority of the transport mobility strategy is focused on passenger transport and most of the references to freight relate to modal shift
Environmental	Transport relies on road mode

Source: Tölke and McKinnon, 2021 [16]

4 Policy Review and Analysis for HGV Decarbonisation in Ireland

4.1 Overview of National Policies and Initiatives

- **Climate Action Plan:** Ireland's Climate Action Plan sets targets to reduce greenhouse gas emissions across various sectors, including transport. It aims to transition to a low-carbon economy, promote electric vehicle adoption, and establish support for the decarbonisation of HGVs [17].

- **EU Directives:** Ireland is obligated to follow various European Union directives related to transport emissions reduction. The Alternative Fuels Infrastructure Directive and the RePowerEU initiative encourage the deployment of alternative fuels infrastructure, including electric vehicle charging stations, hydrogen refuelling stations, and natural gas filling stations [18].
- **The TEN-T policy** of the European Union plays a pivotal role in establishing a comprehensive and efficient transport infrastructure network across the EU. The policy's objectives encompass facilitating the smooth movement of people and goods, enhancing accessibility to employment and services, promoting trade and economic development, and reinforcing social and territorial cohesion within the EU. Additionally, the TEN-T policy places a strong emphasis on reducing the environmental impact of transportation, while simultaneously enhancing safety and the overall resilience of the transport network [19].
- **RED II:** Ireland is committed to meeting the requirements of the Renewable Energy Directive II (RED II). This directive aims to increase the share of renewable energy in transport, promoting the usage of sustainable biofuels, renewable hydrogen, and renewable electricity for transport purposes [20].

5 Policy Recommendations

Accelerating the decarbonisation of HGVs in Ireland requires well-designed and comprehensive policy interventions that can drive the adoption of zero-emission HGVs.

Establishing Regulatory Frameworks and Setting Targets: The European Commission's proposed amendments aim to enforce stricter CO_2 emission standards for heavy-duty vehicles from 2030 onwards, extending coverage to smaller trucks and buses, thereby promoting cleaner technologies and low-emission vehicle development. By establishing specific emission caps like CO_2 limits, manufacturers are incentivised to create and market low-emission vehicles [21]. This will promote the gradual phase-out of internal combustion engine HGVs and promote the transition to zero-emission alternatives.

Financial Mechanisms and Incentives to Support HGV Decarbonisation: Transport & Environment UK, via Element Energy (an ERM Group company), studied accelerating battery electric truck adoption in Great Britain, optimising charging methods. Taking a cue from this study, Ireland government should provide grants and subsidies for the purchase of zero-emission HGVs and charging/infrastructure installation, reducing the upfront costs for operators and encouraging faster adoption. Also, tax Incentives like exemptions or reductions on road tax, toll fees, and parking charges for zero-emission HGVs making zero-emission options more financially attractive to fleet operators [22].

Integration into Broader Sustainable Transportation Strategies: Promoting multimodal transport integration involves combining HGVs with rail, inland waterways, and alternative modes to reduce road dependency and enhance last-mile delivery using zero-emission vehicles. Intermodal solutions, as outlined by UNCTAD, optimise infrastructure use, boost logistics performance, cut inventory costs, and facilitate market connectivity [23]. Collaboration, according to IEA [23], is essential as international cooperation is vital for expediting the decarbonisation process, ensuring timely progression towards a zero-emission HGV sector, and aiding in achieving sustainable transport goals [12].

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A Feasibility Study on the Italian Road Transportation Capability to Meet the 2030 EU Decarbonization Targets

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Abstract. This work focuses on the analysis of future feasible 2030 scenarios of the Italian vehicle fleet in view of the decarbonization targets agreed within the "Fit for 55" package. This was done through a calculation model of the Italian road fleet's Well-to-Wheel GHG emissions and energy consumption of the energy carrier supply chains. The same EU targets for the sectors covered by the Emission Trading System was assumed (−43.7% GHG emissions compared to 2005).

In a deep uncertainty contest, two different scenarios have been built up to represent the upper and lower bound of a range in which the real 2030 scenario will be placed. The model has been validated simulating the 2019 scenario against the official Italian database on energy carrier market. The 2030 predictions demonstrate that the actual trends and policies appears not enough for the target matching. However, with the introduction of trend breaking actions, based on the massive introduction of green vehicles and biofuels, Italy might be able to achieve encouraging reductions in WtW based GHG emissions; up to 40% with reference to 2005.

Keywords: Well-to-Wheel analysis · GHG emissions · Italian road transport · Vehicle electrification · Bio-fuels · Decarbonization paths

1 Introduction

The greenhouse gas emissions represent a serious problem toward which much attention is being paid. In Italy, in 2019, the transport sector was responsible for the 25% of the CO_2eq emissions, 90% of which were due to the road transport [1, 2]. The European

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committee is establishing a series of proposals, namely Fit-for-55, to reduce the GHG emissions by, at least, 55% in 2030 compared to 1990. In Italy, all the sectors covered by Emissions Trading System (ETS) among which the road transport lies, will have to provide an overall reduction of their environmental impact by the 43.7% compared to 2005, in 2030 [3]. So, there is not a particular law that specifies the objective for the Italian road transport sector; however, a question comes to mind: can it reduce its GHG emissions by at least a 43.7% assuming an equal distribution of reduction gap?

The present work's aim is to verify the Italy capability to meet the 2030 target from both Tank-to-Wheel (TTW) and Well-to-Wheel (WTW) point of view as the EU targets, now focused on TTW cycle, are being reviewed and they could be shifted toward a WTW analysis. TTW considers the emissions and consumption provided by the vehicles on road as WTW extends further the analysis to the energy carrier supply chain (fuel or electricity). To this aim a calculation model, based on energy carriers and vehicle feature database, has been setup to characterize the GHG emissions and energy consumption of the actual vehicle fleet; and it is versatile enough to estimate future scenarios.

2 Methodology

To get the highest possible accuracy evaluating the Italian fleet scenarios and the actions to take to reach the target, a Bottom-Up approach is needed, starting from a deep segmentation of the fleet as input. The vehicle fleet has been segmented as showed in Fig. 1.

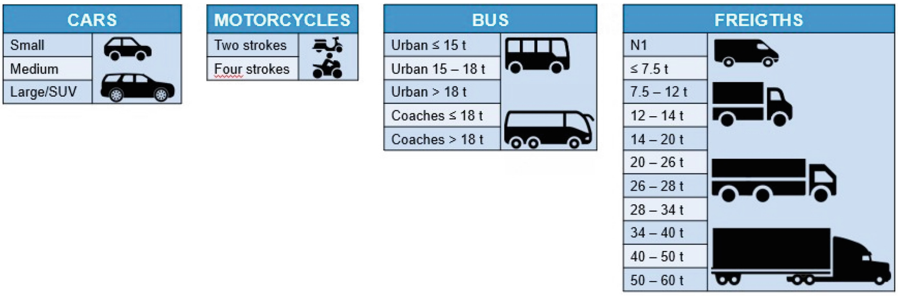

Fig. 1. Road vehicle fleet segmentation.

Each category in Fig. 1 is subsequently divided per Euro category, trip contest (Urban, Rural, Highway) and fuel/energy source used (Diesel, gasoline, GPL, electricity etc.).

The analysis of the reference 2019 and 2005 scenarios has been the first step. The 2019 situation is the most recent year (not affected by covid pandemic) for which there are many sources for the results to be compared to, and represents the starting point to evaluate the 2030 forecasts; while 2005 is the reference scenario for the targets.

Predicting the future 2030 scenario is a very difficult task; there might be an infinite number of combinations of factors, policies, technologies and energy vectors that might lead to the precise scenario. In this deep uncertainty contest, two 2030 scenarios have been hypothesized. All the realistic and highly favourable to decarbonization hypothesis were merged to build up the 2030 "Maximum Decarbonization" (Max Decarbo) scenario, while all the realistic assumptions less favourable to the decarbonization were merged to create the "Minimum Decarbonization" (Min Decarbo) scenario. Both scenarios are very improbable as it is unlikely to happen that all the assumptions highly or less favourable to decarbonization will occur; they represent the extremes of a range in which the actual 2030 scenario will be.

2.1 Reference Scenarios

Several Italian official sources have been consulted for establishing the vehicle fleet demand in 2019. However, they do not allow a complete and unique reconstruction for various reasons, making the reconstructed fleet original and in need of validation. The Bottom – Up approach is finalized to the calculation of the yearly TTW and WTW energy consumptions and GHG emissions, indicated in the following, as usually done, as equivalent CO_2 emissions (CO_2eq). The vehicle mileages as vehicles*km (vehkm) of each category and sub-category, trip context and energy source are the input to the main formulas applied for both TTW and WTT analysis:

$$TTWCO_{2eq}[g] = CO_{2eq}[g/km] * Vehkm[km] \quad (1)$$

$$TTW[kWh] = EC[kWh/km] * Vehkm[km] \quad (2)$$

$$WTTCO_{2eq}[g] = WTTCO_{2eq}[g/kWh_{fuel}] * EC[kWh/km] * Vehkm[km] \quad (3)$$

$$\text{WTT}\ [kWh] = WTT[kWh/kWh_{fuel}] * EC[kWh/km] * Vehkm[km] \quad (4)$$

The specific coefficient CO_2eq [g/km] and EC [kWh/km] refer to specific emissions and energy consumptions of the vehicles. They derive from the ISPRA 2019 database [4], Real Driving Emissions (RDE) data, ICCT report [5], appropriately increased homologation data published by the vehicle manufacturers or provided by a homemade developed Matlab algorithm based on the energy spent during a homologation test. Formulas 1 and 2 allow to calculate the yearly TTW fleet GHG emissions and energy consumption, and subsequently the total fuels consumption.

In formulas 3 and 4, used for the WTT analysis, two specific coefficients are introduced, namely WTT CO_2eq [g/kWh$_{fuel}$] and WTT [kWh/kWh$_{fuel}$], typical of each energy source. They are the amount of CO_2eq or energy needed to produce and distribute a unit of fuel on road. They primarily derive from JRC [6]. Summing up the WTT and TTW analysis' results, the WTW ones are achieved.

To validate the model, the amount of each fuel sold on road provided by the Ministry of Ecological Transition (MITE) [7] has been compared to the respective quantities calculated. Similar approach is used for the reference 2005 scenario.

2.2 2030 Scenarios

To establish the fleet composition of the 2030 scenarios, several assumptions have been made through the ASI (Avoid, Shift, Improve) approach. In particular, the market trends, expected policies and regulations have been considered for both the two scenarios. For sake of brevity, the differences between the two scenarios can be resumed as the Max Decarbo scenario assumes stronger measures to reduce travels (e.g. enhancement of smart working or higher freights filling ratios etc.), a greater shift towards more sustainable transport modes (e.g. encouragement of shared mobility or public transportation etc.) and a marked fleet improvement towards greener vehicles (e.g. high fleet penetration of BEV, HEV and PHEV cars and H_2 long haul trucks) than the other one. Second generation biofuels have been considered too, as the Italian law prescribes, for both scenarios. The two most mature biofuel technology have been considered: the Hydrotreated Vegetable Oil (HVO) and Compressed Bio Methane (CBM). The Italian regulation [8] imposes 1 million of tons share for HVO and 1.1 billion of m^3 share of CBM. These quantities have been optimistically assumed fully used for road transport and assigned to the Min Decarbo scenario, while a higher share has been introduced in the Max Decarbo one (2 million of tons for HVO and 1.5 billion of m^3 for CBM). It is important to underline that biofuels bring high advantages in the WTT analysis, in accordance with the JRC methodology [6], and negligible gains in the TTW results. CBM substitutes CNG for all vehicles, HVO substitutes Diesel for EURO 6/VI vehicles; without any particular policy on preferable usage paths. The main reference used to analyse the different trends is the “Piano Nazionale Integrato per l’Energia e il Clima” (PNIEC) [9].

2.3 2030 “Trend Breaking” Scenarios

The potentialities of biofuels in impacting the WTW results have been deepened by introducing two “trend breaking” scenarios, also referred to as “MaxBio” scenarios. There is no trend or policy that might lead to shares of HVO and CBM higher than the ones hypothesized for the 2030 regular scenarios. However, according to the main Italian stakeholders it might be possible to further stretch the biofuels market share, reaching about 4.5 million of tons for HVO and 3.5 billion of m^3 for CBM in 2030. By the way, it was assumed that the effectiveness of the MaxBio to match the targets seems facilitated by the existing capillary refuelling infrastructure and the relevant fleet share of both Euro VI diesel and gas vehicles in 2030.

The “MaxBio” scenarios have the same fleet composition than the “tendential” (non-trend breaking) 2030 scenarios, but policies specifically targeted at the freights sector have been applied. Heavy Duty Vehicles (HDVs) are not expected to benefit from extensive electrification or a large shift towards hydrogen fuel (that will impact only the long haul HDVs on 2030), meaning that the freight sector is “hard to abate”. Then HVO has been specifically used to substitute Diesel for the EURO VI HDVs in both “MaxBio” scenarios; and CBM is used to substitute the CNG vehicles. Any remaining quantity is eventually distributed towards the rest of the fleet.

3 Results

In the following paragraphs, the model validation for 2019 and the 2030 scenarios are reported. For brevity reasons, selected results will be discussed.

3.1 2019 Validation

In Fig. 2, the 2019 TTW emissions results provided by the different vehicle categories are reported.

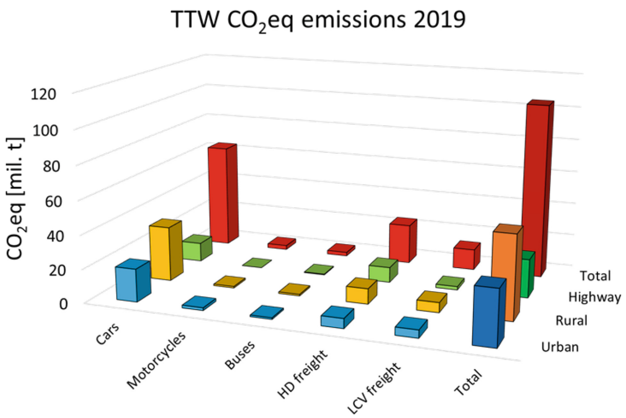

Fig. 2. Model TTW results for the GHG emissions in 2019.

The total amount CO_2eq emitted in 2019 is about 104 million tons. The most of it comes from cars and from the rural trip, followed by urban one. The urban contest occupies a 20% share of total mileage, but it moves to a 31% of CO_2eq share due to the higher specific emissions and consumptions provided by Internal Combustion Engine (ICE) vehicles. Same considerations can be made for freights (LCVs + HDVs); against a mileage share of 18% on the total mobility demand, their emissions share is up to 35%.

The results from the Bottom-Up approach are compared with the registered fuel market in 2019 in Table 1 to validate the procedure.

Table 1. 2019 amount of fuel sold for road transport versus model results.

Fuel	Model output	Fuel sold	Percentage difference
Gasoline [mil. L]	9 704	9 837	-1.1%
Diesel [mil. L]	30 461	28 465	+7.0%
LPG [mil. L]	2 643	3 006	-12.1%
CNG [mil. Kg]	736	786	-6.4%

Looking at the very low percentage differences; in particular for Diesel and Gasoline (the most consumed fuels) it can be appreciated the procedure reliability.

3.2 2030 Predictions

In the following Figures, the fleet compositions for both scenarios are reported (Fig. 3).

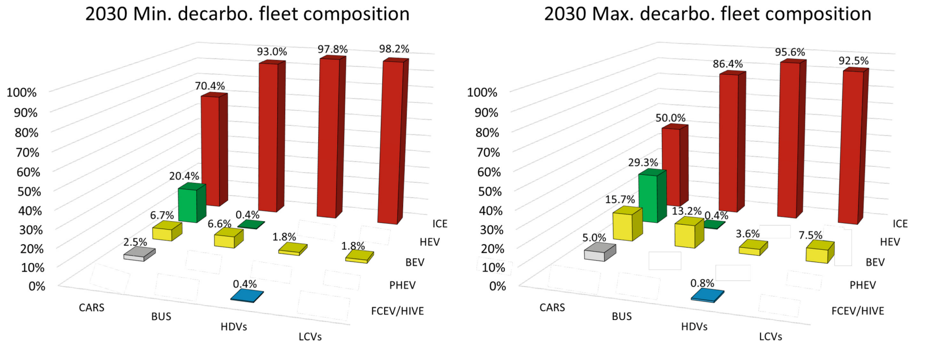

Fig. 3. Vehicle fleet composition for Minimum and Maximum Decarbonization scenarios

ICEs are the most spread technology for both scenarios, but in the Max Decarbo the higher efficiency low emissive technologies (BEV, H_2 etc.) have higher penetrations, although, as said, it is a highly unlikely scenario.

In Fig. 4, the correspondent TTW and WTW CO_2eq results are shown, together with the MaxBio scenario.

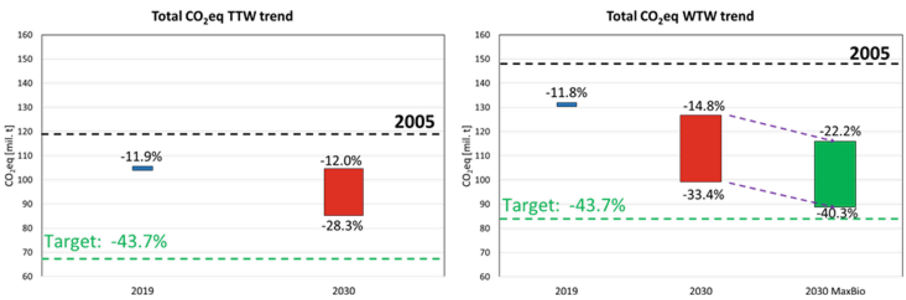

Fig. 4. TTW and WTW analysis emissive results, compared to 2005 reference scenario.

The expected 2030 total GHG emissions is within the interval between the extremes represented by the “MinDecarbo” and “MaxDecarbo” scenario.

It is interesting to note that in 2019 the WTW reduction is 0.1% lower than TTW, due to the low BEV cars share that provides null emissions in TTW but impact the WTT phase. In 2030, this trend is inverted; higher reductions have been reached for WTW due to the biofuels share in the tendential scenarios. However, the reductions achieved without trend breaking policies are far from the 43.7% target mainly due to the freights contribution share increase with respect to 2019 (43% vs 35%), proving its "hard to abate" characteristic. The "MaxBio" scenarios allow to reduce the gap from a WTW 2030 target; with the highest reduction achieved equal to 40.3%. The policies adopted also permit to reduce the freights contribution share to 34%, highlighting biofuels capabilities in reducing the environmental impact of the fleet.

4 Conclusions

This study provided estimations of both GHG emissions and energy consumption of the Italian road transport sector in 2030. The deep uncertainty in making 2030 predictions has been considered developing two different tendential scenarios that represent the extremes of a range inside which the actual 2030 will be placed. Italy will not be able to get close to the 43.7% reduction with reference to 2005, neither on TTW and WTW cycle, without trend breaking policies. The "MaxBio" scenarios have proved the high efficiency in reducing the fleet environmental impact through a proper combination of green energy carriers like electricity for BEVs and biofuels for the remaining vehicles of the fleet, while hydrogen will give marginal contribution for the observed timeframe.

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Towards Zero Emission Mobility in Ireland: Life Cycle Assessment of Moving Green Hydrogen

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Abstract. In Ireland, transportation accounts for 36% of total energy consumption, mainly due to private cars and heavy goods vehicles, responsible for 70% of transportation sector carbon emissions. Despite some progress in new car carbon intensity, petrol and diesel vehicles remain dominant. Hydrogen (H_2) is a non-toxic, highly combustible gas, holds significant potential, especially for heavy-duty vehicles, as a mean to reduce carbon emissions. However, realising this transition requires targeted policies and infrastructure development.

A crucial tool for evaluating hydrogen-based transportation is a comprehensive life cycle assessment (LCA). This assesses the full process, from production, transport and use, to disposal, providing insights into environmental impact, including carbon footprint, energy consumption, air pollution, material use and vehicle efficiency. By assessing different hydrogen sources like green and blue hydrogen, the LCA informs decision-makers and aids in developing sustainable transportation strategies.

This work highlights the importance of the method to transporting the hydrogen fuel. Fuelling stations show a substantial carbon footprint (1.75 kg CO_2 eq./kg H_2), while hydrogen transportation through pipelines has minimal emissions (0.0000235 kg CO_2 eq./kg H_2) compared to moving it in compress cylinders by diesel truck. This underscores the need for careful planning to minimise environmental impacts when deploying hydrogen in transportation systems.

Keywords: green hydrogen · transport · life cycle assessment · CO_2 emissions

1 Introduction

Climate change, driven by GHG emissions from fossil fuels, requires urgent solutions. The Paris Agreement and IPCC have underscored the need to limit warming to 1.5 °C [1, 2]. Transitioning to cleaner renewables, like wind power, offers eco-friendly benefits and energy security. Republic of Ireland relies significantly on wind energy, just over 300 wind farms totalling 4,332.5 MW capacity in 2022 [3]. However, wind energy's reliability depends on weather conditions, impacting yearly generation. The growth of variable renewables has fuelled interest in hydrogen as a long-term electricity storage solution that can also decarbonise other sectors [4].

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1.1 Transportation Challenges

For the case of Ireland, the transport sector in Ireland accounts for nearly 12 Mt CO_2,eq in 2022 [5], positioning it as the second-highest emitting sector, closely following the agricultural sector. Diesel retained its dominant position as the largest fuel type, comprising 70% of the total, followed by petrol at 15% and jet kerosene at 10% in 2022 [6].

1.2 Heavy Goods Vehicles (HGVs)

Heavy goods vehicles (HGVs), also known as commercial trucks, contribute to 14% of Ireland's road transport emissions, equivalent to 1.6 MtCO_2eq, with the majority powered by diesel fuel. Approximately 61% of HGVs in Ireland were 10 years old or younger as of the end of 2022 [7]. On average, a long-distance HGV emits about 102.9 g of CO_2 per tonne-kilometre [8].

The H2Haul project [9] has demonstrated that there is a possibility for fuel cell trucks to make up approximately 17% of the new truck sales in 2030. This projection is based on a significant reduction in technology costs. As the production of fuel cell hydrogen trucks increases and the cost of hydrogen falls below 6 EUR/kg, these fuel cell hydrogen-fuel cell heavy-duty trucks offer operational performance that closely matches diesel trucks in terms of daily range, refuelling speed, payload capacity, and total cost of ownership. In Ireland, during an 8-week trial period on Irish roads, a hydrogen fuel cell electric bus covered a distance of 3,086 km. This bus, with a refuelling time of under 9 min and a range of 400km, garnered significant approval from the traveling public, as indicated by passenger satisfaction surveys [10]. Wróbel et al. [11] found that hydrogen internal combustion engines (ICEs) are cost-effective and practical for specific vehicle applications, particularly in construction and agriculture. Although they emit nitrogen oxides and require exhaust gas treatment, hydrogen ICEs adapt well to varying hydrogen quality and exhibit reliability in demanding conditions. Their potential for reducing urban CO_2 emissions is significant but hinges on hydrogen infrastructure and regulatory advancements. Zhang et al. [12] introduced a collaborative planning model to promote hydrogen vehicle adoption, integrating energy, hydrogen, gas, and transportation systems to reduce carbon emissions through green hydrogen production. This model optimises hydrogen vehicle traffic flow and hydrogen station locations, minimising congestion and travel time within the integrated network, thus lowering carbon emissions and traffic duration.

1.3 Role of Hydrogen in Decarbonisation

Hydrogen, despite being the most abundant element in the universe, is typically found in compounds like water and hydrocarbons due to its small molecular size. Producing hydrogen involves breaking these chemical bonds and storing the hydrogen, requiring energy input, often in the form of electricity or heat. It has been proved that it is the clean, light, and most highly flammable fuel on combustion producing only water. The source of this energy input and the resulting by-products influence the carbon footprint of hydrogen production.

Hydrogen can be generated using various methods, each with different technological maturity levels, environmental impacts, and greenhouse gas emissions [13]. One such method is electrolysis, which uses electrical energy to split water molecules into hydrogen and oxygen, with oxygen being a by-product. When renewable energy sources like wind or solar power the electrolysis process, it produces high-purity hydrogen with no associated CO_2 emissions, often referred to as "green hydrogen".

1.4 Present Research, Aims and Objectives

Extensive literature review reveals the significant potential of hydrogen for transportation. Hydrogen can be produced on-site or off-site, with various transportation technologies to refuelling stations. Economic analyse is crucial to assess viability and technical intricacies.

Life Cycle Assessment (LCA) is used for the evaluation of the environmental impact across the product's entire lifecycle, from raw material acquisition to disposal. This includes processes like generating green hydrogen from wind power via water electrolysis and subsequent transport and compression for refuelling. This research investigates two distinct hydrogen transportation scenarios, focusing on delivering hydrogen from production hubs to refuelling stations for convenient vehicle refuelling.

2 Methodology

Life Cycle Assessment is a systematic approach to assess the ecological impact of products, processes, or projects from raw material extraction to disposal. It is crucial for sustainability evaluations. LCA involves Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. LCA guides informed decisions to reduce environmental impact. In this study, GaBi software for LCA is utilised.

The objective is to develop a comparative LCA of a hydrogen production system, starting from renewable energy (wind turbines) to the fuel filling station, considering two transportation methods: trucks and HDPE pipelines. The cradle-to-gate and gate-to-gate processes in two scenarios as examined, as shown in Fig. 2. The study's boundary includes energy consumption for transportation and hydrogen compression (Fig. 1).

The description outlines two modelling scenarios. Both start with 'Electricity from Wind Power,' a clean and renewable source, powering a highly efficient 50 KW Proton exchange membrane (PEM) electrolyser for hydrogen production.

Scenario 1 transports hydrogen via 'GLO Trucks Euro 5,' considering environmental impacts. It ends at the refuelling station. In contrast, Scenario 2 explores hydrogen transportation via pipelines, using polyethylene material data from external sources. Both approaches assess environmental impacts and sustainability throughout the hydrogen production and transportation life cycle. The simulation process for both scenarios is developed using Gabi software, is presented graphically in Fig. 2.

This schematic offers a clear representation of the sequential stages involved in Scenario II, where wind power is the energy source for green hydrogen production and a pipeline system is utilised for the transportation of the produced hydrogen to the hydrogen refuelling station. Since the approach is hypothetical, the distances for the transportation

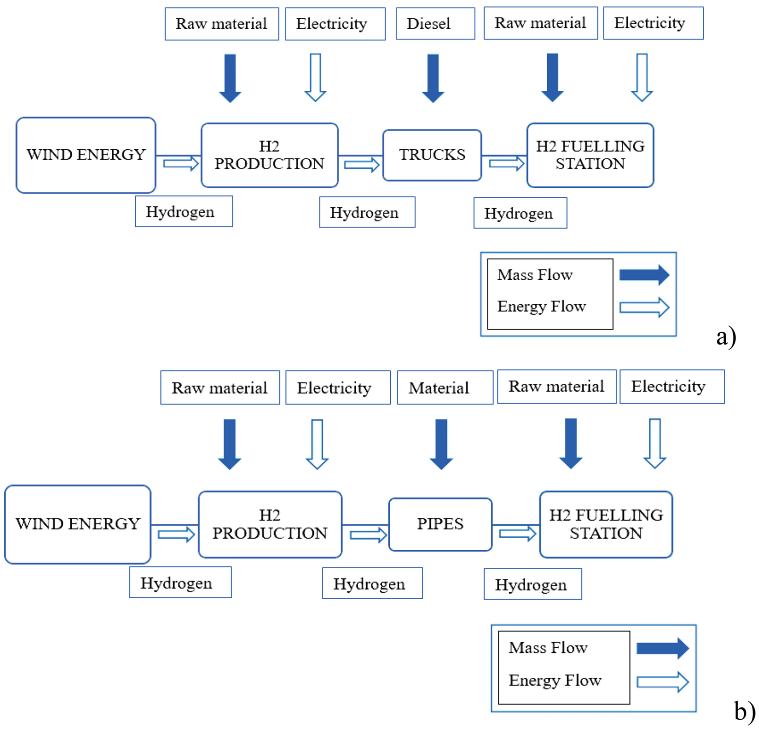

Fig. 1. System boundary of Life Cycle Assessment of hypothetical hydrogen system, a)using trucks, b) using pipeline

of hydrogen from the production subsystem to the fuelling station subsystem is taken as 6km.

Furthermore, Table 1 provide the inventory data for the utilised electrolyser and refuelling station, respectively. Notably, all materials employed in the simulation are presented in terms of kilograms per kilogram of hydrogen produced. It is worth mentioning that that we used database for the subsystem: electricity from wind power, diesel, and trucks from GaBi software for the diesel truck, and the life cycle inventory data for the hydrogen pipeline consists of just 1.37 E-5 kg of polyethylene after normalising with 1 kg of Hydrogen.

Examining the PEM electrolyser in particular, it is evident that cast iron stands out with an approximate usage of 8 g per kilogram of hydrogen. Additionally, it is worth noting that the assumption here is that the production of 1 kg of hydrogen consumes 10 kg of fresh water. Turning attention to the refuelling station, the predominant materials are low alloy steel, followed by high alloy steel in terms of usage.

Table 1. Life Cycle Inventory Data for PEM Electrolyser and for fuelling Station

Electrolyser		Fuelling Station	
Materials	Mass	Materials	Mass (kg)
Aluminium	0.00105 kg/kg H_2	Low alloy steel	0.07889 kg/kg H_2
Cast Iron	0.008 kg/kg H_2	High alloy steel	0.0081 kg/kg H_2
Polyethylene	0.0015 kg/kg H_2	Cast iron	0.0023 kg/kg H_2
Steel Billet	0.0037 kg/kg H_2	Copper	0.000910 kg/kg H_2
Graphite	0.0045 kg/kg H_2	Aluminium	0.000384 kg/kg H_2
Polypropylene Granulate	0.0025 kg/kg H_2	Polymer	0.00028 kg/kg H_2
Polyvinylidenchloride Granulate	0.0011 kg/kg H_2	Carbon fibers	0.00135 kg/kg H_2
Steel	0.0011 kg/kg H_2	Electricity	14.2 kWh/kg H_2
Fresh Water	10 kg/kg H_2	Hydrogen	1 kg
Electricity from wind	180 MJ/kg H_2		

3 Result and Discussion

The environmental performance throughout the life cycle is characterised by quantifying the environmental effects using indicators such as Global Warming Potential over a 100-year horizon (GWP), Ecotoxicity Potential (ETP), and Acidification Potential (AP) as developed by CML 2001 – JAN 2016.

The assessment comprises two scenarios: one utilising electricity sourced from wind power and transporting the generated hydrogen by diesel-fuelled trucks to the fuelling station (Scenario 1) and the other relying on electricity from the pipeline to transport hydrogen to the refuelling station (Scenario 2). The results indicate that Scenario 2 has a lower environmental impact when compared to Scenario 1. A comprehensive breakdown of the inflow and outflow of the hydrogen systems can be found in Table 2.

Table 2. Breakdown of the inflow and outflow of the hydrogen systems

INPUT	SCENARIO 1	SCENARIO 2
Resources	1.3×10^3kg	1.3×10^3kg
OUTPUT		
Deposited Goods	3.09 kg	3.09 kg
Emissions to air	22.9 kg	22.6 kg
Emissions to freshwater	1.32×10^3kg	1.3×10^3kg
Emissions to seawater	2.38 kg	2.37kg
Emissions to agricultural soil	4.03×10^{-6}kg	4×10^{-6}kg
Emissions to industrial soil	1.34×10^{-5}kg	1.34×10^{-5}kg

3.1 Contribution Analysis

The contribution analysis helps to analyse the results of the life cycle of the hydrogen system by evaluating the contribution of polluting elements to the surroundings. From the Table 3, it is visible that the Scenario 2 has less emissions compared to the Scenario 1. It can be interpreted that the trucks cause more pollution to the environment than the pipelines. The most significant pollution is observed in the marine aquatic system potential in both scenarios with the value 210 kg DCB eq per kg of H_2. This is due to the extraction of fresh water for hydrogen production through electrolysis. Moreover, the sources of grid electricity in Ireland varies from renewable, waste, natural gas etc. The most minor pollution is Ozone Depletion Potential with the value 6.21E-13 kg R11 eq per kg of H_2, which is negligible.

Table 3. LCA results for the proposed two scenarios in the present work

Emission/kg H_2	Scenario 1	Scenario 2
GWP 100 years (kg CO_2 eq.)	2.17	2.14
AP (kg SO_2 eq.)	3.14×10^{-3}	3.36×10^{-3}
EP (kg Phosphate eq.)	3.84×10^{-4}	3.69×10^{-4}
ODP, steady state (kg R11 eq.)	6.21×10^{-13}	6021×10^{-13}
ADP elements (kg Sb eq.)	1.1×10^{-5}	1.1×10^{-5}
ADP fossil (MJ)	25.1	24.8
FAETP inf. (kg DCB eq.)	4.69×10^{-3}	4.58×10^{-3}
HTP inf. (kg DCB eq.)	0.713	0.713
MAETP (kg DCB eq.)	210	210
POCP (kg ethene eq.)	2.66×10^{-4}	2.83×10^{-4}
TETP (kg DCB eq.)	0.0222	0.0222
GWP exc. Bio (kg CO_2 eq.)	2.16	2.14
GWP inc. Bio (kg CO_2 eq.)	2.17	2.15
GWP LUC (kg CO_2 eq.)	1.3×10^{-3}	1.13×10^{-3}

3.2 Dominance Analysis

The most impacting process in the hydrogen system can be identified through the dominance analysis. The graph below represents the global warming potential polluting processes in the system. The filling station has a significant quantity among the others with a value of 1.75 kg CO_2 eq./kg H_2. The least emitting process is the transportation through pipelines with 0.0000235 kg CO_2 eq./kg H_2. The trucks and the hydrogen production exhibit certain quantities of carbon dioxide equivalent to the atmosphere.

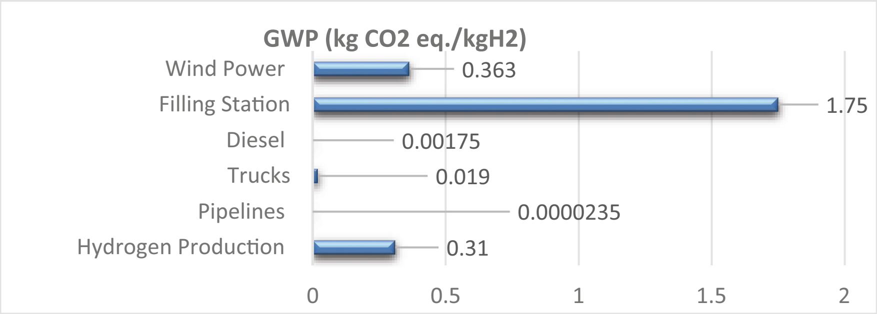

Fig. 2. Global warming potential of the main stages in the system

4 Conclusion

Hydrogen exhibits substantial potential as a transportation fuel, but its utilisation requires thorough examination. It can be produced on-site or off-site, utilising various transportation technologies to reach refuelling stations, necessitating rigorous economic and technical analyses. This research employs LCA to comprehensively evaluate the environmental impact of hydrogen production and transportation, focusing on indicators like GWP, ETP, and AP.

The study explores two scenarios: Scenario 2, using pipeline for moving hydrogen, shows lower environmental impact than Scenario 1 with diesel trucks. In conclusion, hydrogen holds promise for transportation, but careful consideration of production and transportation methods is essential to minimise environmental impacts. Scenario 2 exhibits a better environmental profile. This research underscores the importance of tools like LCA and specific impact indicators for informed decision-making in transitioning to hydrogen-based transportation systems.

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Does Eco-Routing Even Work? Some Experimental Findings

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Abstract. We live in an ever-changing world. The increasing urbanization rate has resulted, among others, in an increase in private vehicles ownership and usage. The research focuses on eco-driving and its potential to reduce greenhouse gas emissions in urban areas with high private vehicle usage. The proposed framework, called FERPS uses unsupervised machine learning techniques to categorize driving behavior into three trip-based profiles. A fuel consumption model is then employed using Gradient Boosting Decision Trees algorithm to estimate fuel consumption for upcoming trips based on dynamic driving profiles, vehicle data, and trip characteristics. FERPS is then implemented in in the inner-ring urban transport network of Athens, Greece, using the SUMO microscopic simulator. Eleven scenarios, including a BAU scenario and various FERPS penetration rates, are simulated during the morning peak hour. Emissions-related KPIs are measured for comparison and the results indicate that higher FERPS penetration rates lead to reduced emissions, highlighting the potential benefits of eco-driving in urban transport networks. By providing personalized eco-routing information, FERPS aims to promote environmentally friendly driving behavior and contribute to overall emission reduction efforts.

Keywords: Eco-driving · fuel efficiency · GHG emissions · personalized routing · eco-routing · impact assessment

1 Introduction

Reducing the impact of human-induced climate change is a key priority for the UN and the EU [1, 2]. The transport industry is the largest contributor to Green House Gas (GHG) emissions, accounting for approximately 30% of all anthropogenic emissions [3].

Eco-driving can be defined as the adoption of a driving behavior that aims at saving fuel and reducing GHG emissions [4]. It can reduce fuel consumption by up to 25% and GHG emissions by at least 30% [5]. Eco-routing is one of the strategies assisting eco-driving. The idea is to minimize fuel consumption by selecting an optimal route for a given set of origin and destination [6]. The development of eco-routing algorithms

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has gained considerable attention. Many researchers found that the use of pre-trip eco-routing navigation systems leads to reduced fuel consumption and emissions, spanning from 4% [7] to 46% [8].

The present research aims at proposing and testing an innovative pre-trip eco-routing methodological framework by using naturalistic driving data, open-source software and microscopic traffic simulation. The paper is structured as follows: Sect. 2 presents the methodological approach followed for developing said eco-routing framework. In Sect. 3, the implementation of the approach, as well as some significant results, are presented. Finally, conclusions and future research directions are given in Sect. 4.

2 Methodological Approach

In the present section, the methodological approach behind the "Fuel Efficient Route Planning System" – FERPS framework developed in this research is presented. First, the overall driving behavior of each driver is detected using k-means clustering, an unsupervised learning algorithm to identify driving behavior on a trip level, and, based on statistical analysis, the overall driving profile of each user is defined. Then, a supervised learning algorithm, Gradient Boosting Decision Trees, is deployed; it predicts the fuel consumption considering the driving profile of each user as well as trip-based attributes. It is worth-noting that both the driving profile of each user and the trip-based attributes are variables that can be estimated a priori.

Next, for a given set of origin and destination coordinates in a given graph, the Open Source Routing Machine (OSRM) Application Programming Interface (API) and the Opentopodata API were used to estimate the alternative routes together with their trip attributes. Then, the fuel consumption model was deployed to assign a specific fuel consumption value to each alternative route and the most eco-friendly one was given as recommendation to the user.

Finally, FERPS is evaluated at different penetration rates by gradually increasing its application to the total number of routes in the Athens testbed. The evaluation involves a progressive increase of 10% of the service penetration rate. By comparing the total emissions generated during these stages with those from the Business-as-Usual (BAU) scenario, the system's performance and environmental benefits are thoroughly assessed.

3 Implementation and Results

3.1 Athens Testbed

Athens Testbed consists of 1220 nodes and 2556 edges, and it is implemented as a graph using the networkx Python library. Demand-wise, 86053 routes with known origin and destination are applied to the network. Additionally, the speed limits of the edges and the coordinates of the nodes are used. By utilizing OpenTopoData API the corresponding altitudes of the nodes are considered. Athens Testbed is illustrated in Fig. 1.

Fig. 1. Athens Testbed.

3.2 Development of FERPS

In this section, the methodology for developing FERPS is described. The proposed approach tries to provide a user agnostic approach of describing a trip and a driver by clustering trips based on the behavioral features to produce user agnostic driving profiles, and assigns to each driver a characterization that stems from the average characterization of his trips. For the drivers' profiling we apply a k-means clustering algorithm on the features seen in Table 1. Sample size is 2243 trips conducted from 20 drivers.

Table 1. Features used for k-means clustering algorithm.

Variable	Unit
Average acceleration	km/h/s
Average deceleration	km/h/s
90% percentile of acceleration	km/h/s
90% percentile of deceleration	km/h/s
% of trip duration the driver engaged in harsh acceleration events	%
% of trip duration the driver engaged in harsh deceleration events	%
% trip duration the driver was driving over the speed limit	%

Following the Elbow rule, the optimum number of clusters is 3. Figure 2 shows the distortion in the results in relation to different values of k in the k-means algorithm. Clustering is evaluated using the Dunn index, which is the ratio of the smallest distance between observations not in the same cluster to the largest intra-cluster distance. The value of Dunn Index is 1.345 and indicates a good clustering since it is larger than 0. Further, we use the centroids to provide a characterization for each cluster.

The resulting profiles, as well as other route specific information (altitude, distance, and duration), are introduced in a fuel consumption model, based on Gradient Boosting Decision Trees. The above is route specific information that can be a priori estimated for given origin and destination. OSRM API was used to derive trip related information,

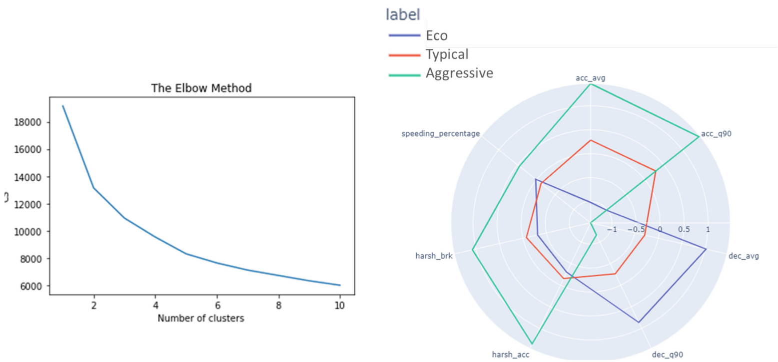

Fig. 2. Identification of the number of clusters using the Elbow method and the clusters' centers.

and the altitudes are retrieved by the EU-DEM dataset. The trained model provides fuel consumption predictions with MAPE 9.3% (test set). The feature importance and impact on fuel consumption appear in Fig. 3.

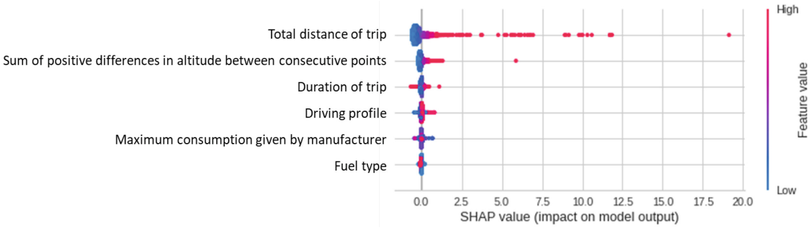

Fig. 3. SHAP values of all variables included in the fuel consumption model (pre-trip).

Based on the above tools, a pipeline of operations was constructed for providing pre-trip eco-routing information (Fig. 4.). This approach produces an eco-score for every route in the graph. The user then has the opportunity to select a route based on fuel consumption information.

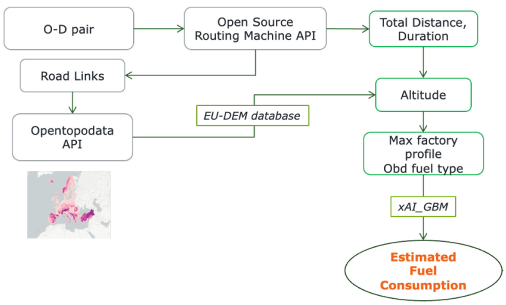

Fig. 4. FERPS pipeline.

3.3 FERPS Impact Assessment

For assessing FERPS, a series of microscopic simulations have been conducted by making use of the SUMO microscopic simulator. Firstly, the BAU scenario is simulated and then FERPS is applied with a 10% gradual increase of its penetration rate. In the end, fuel consumption and GHG emissions produced are compared to the BAU scenario results. Figure 5 illustrates the impact of FERPS in terms of CO2 emissions and fuel consumption reduction, compared to BAU. A CO2 emissions' reduction of approximately 6 tons, and a reduction on consumed fuel by approximately 3000 L is observed for 100% FERPS penetration rate. A reduction of up to 650 g of CO, 80 g of PMx, and 2100 g of NO can also be achieved for the same FERPS penetration rate.

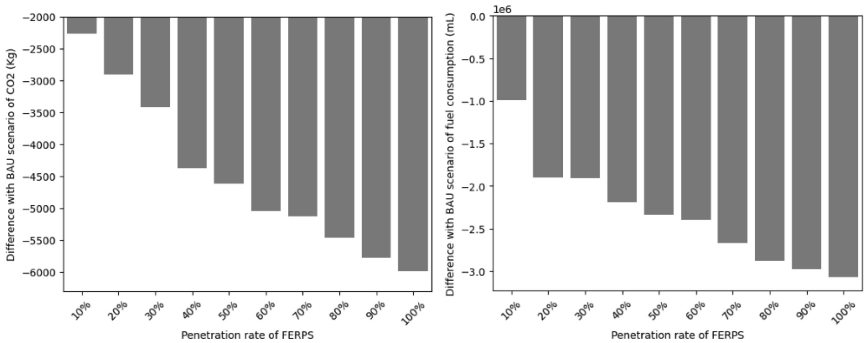

Fig. 5. Difference with BAU scenario for CO2 (left) and fuel consumption (right) for different penetration rates.

Regarding the impact of FERPS on traffic conditions, it can be observed that they are improved after FERPS implementation. An increase in the average speed of the network can be observed (1 km/h for a 100% FERPS penetration rate); it is not significant, but it highlights the positive impact of FERPS on traffic conditions. The same pattern applies in terms of mean travel duration (approximately 200s reduction for 100% FERPS penetration rate). Figure 6 illustrates the impact of FERPS on traffic conditions.

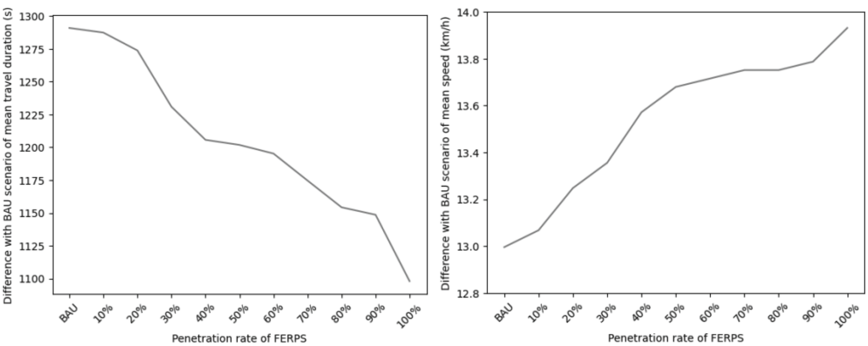

Fig. 6. Impact of FERPS on mean travel duration (left) and mean speed (right).

4 Conclusions

Present research aimed at proposing an innovative pre-trip eco-routing framework. The proposed methodological framework is discussed and its implementation in the Athens Testbed is presented. Based on the results, it is observed that a reduction on fuel consumption and GHG emissions can be achieved by gradually increasing the penetration rate of FERPS. The positive effect of FERPS on traffic flow conditions is also presented. The above methodology can be used as a decision-making tool towards achieving sustainability and conforming with the goal of emissions' reduction in urban road networks. As a next step, FERPS may be applied in other urban or rural road networks for achieving a benchmarking of the presented methodological framework.

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Fuel Cell vs. Battery Electric Buses: Environmental, Economic and Operational Performance

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Abstract. Hydrogen fuel cell buses (FCBs) and battery electric buses (BEBs) represent two types of zero-emission drivetrains for air pollution reduction and decarbonization of public transport. In this work, the two bus technologies are compared in terms of their environmental, economic and operational performance. Real-world data from two European sites serve as basis for a carbon footprint (CF) calculation, a total cost of ownership (TCO) analysis and a performance assessment. The results indicate an advantageousness of BEBs compared to FCBs regarding greenhouse gas emissions and costs. The main reason for the higher climate impact of FCBs is the additional energy required to produce hydrogen, compared to the direct use of electricity in BEBs. The BEBs' advantage in terms of TCO is mainly due to lower vehicle and energy costs. However, the results highly depend on the specific local conditions and assumptions. Furthermore, operation conditions such as range as well as flexibility play a decisive role in bus operators' decision making. Here, FCBs show considerable advantages, making them favorable for long and/or demanding routes.

Keywords: Fuel Cell Buses · Battery Electric Buses · Total Cost of Ownership · Life Cycle Assessment · Performance Assessment · Clean Public Transport

1 Introduction

Cities need to meet air quality and climate targets, and transport is the main cause of urban air pollution and contributes to almost a quarter of Europe's greenhouse gas emissions [1]. Thus, to achieve those targets, transport emissions need to be significantly reduced. An increased use of zero-emission drivetrains as well as a shift from individual mobility to more efficient forms of transport are required [2].

In the European Union, urban and sub-urban buses as a flexible form of public transport have a share of around 56 % of all public transport journeys, with more than 31 billion passenger-kilometers per year [3]. Fuel cell electric buses (FCBs) and battery electric buses (BEBs) as local zero-emission vehicles represent two options to address air pollution and carbon dioxide emissions generated by public local bus transport.

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Partners in the Joint Initiative for hydrogen Vehicles across Europe (JIVE 1 and JIVE 2)[1] are deploying about 300 hydrogen FCBs and the necessary infrastructure in six different European countries. Our work represent a comparative analysis of FCBs and BEBs with regard to their environmental, economic and environmental performance based on real-world data. Data was collected from two JIVE sites and used for a carbon footprint (CF) calculation, a total cost of ownership (TCO) analysis, and a qualitative performance assessment.

2 Methodology

2.1 Input Data

Through the JIVE projects, operational data from over 200 FCBs are continuously being monitored and evaluated. The data analysis has been based on performance indicators defined in the Performance Assessment Handbook [4], including among others the distance driven, hydrogen consumption, refueling time, and availability. In addition, the two considered JIVE sites provided data and information from BEBs deployed in 2022. For site 1, operational data comprises values from 34 BEBs over a period of 7 months. From site 2, average operational values were received. Remaining data gaps were filled with data and information from literature or previous project experiences.

2.2 Boundary Conditions and Bus Specifications

For the CF calculations as well as for the TCO analysis, the operation of one city bus over a service lifetime of 12 years was defined as common functional unit. A 1-to-1 replacement without the use of additional BEBs was assumed. Infrastructure costs were allocated according to the number of buses the infrastructure has been designed for.

At site 1, buses predominantly run in inner city traffic, while at site 2 they are also used in less dense areas, which is particularly noticeable by the significantly higher mileage. Table 1 displays key parameters that serve as basis for the CF and the TCO analysis.

2.3 Carbon Footprint Calculation

To calculate the CF of both technologies, a life cycle assessment (LCA) oriented on the standard EN ISO 14040/44 [5] was carried out. LCA represents a method by which potential environmental impacts associated with a product or service over its entire life cycle (cradle-to-grave) are systematically assessed. This comprises the extraction of raw materials, the production of semi-finished products, the production, the use phase including maintenance and repair, as well as recycling and disposal at the end-of-life, including all respective upstream processes. Maintenance covers regular maintenance activities, such as tire and lubricant changes, and potential replacements of battery and fuel cell. Credits for materials recovered from disposal or energy used in the bus recycling

[1] In the following commonly referred to as the JIVE projects

at the end of its life were not taken into account, in line with common LCA practice in the automotive industry.

Life cycle inventory data were taken from Managed LCA Content (MLC) from Sphera's life cycle assessment software LCA for Experts [6]. As this LCA compares two zero-emission drivetrains, we focused on their impact on climate change, reflected by the global warming potential (GWP, expressed in carbon dioxide equivalents CO_2e) according to Environmental Footprint 3.0 [7].

Table 1. Boundary conditions, bus specifications and assumptions.

Parameter	Site 1 - FCB	Site 1 - BEB	Site 2 - FCB	Site 2 - BEB
Bus type	Double-deck	Double-deck	Solo	Solo
Bus model	Wrightbus Streetdeck FCEV	Optare Metrodecker	Van Hool A330 FC	Ebusco 2.2
Bus length [m]	10.9	10.5	12	12
Bus empty weight [kg]	12,050	11,180	13,755	12,850
Battery type; capacity [kWh]	LTO; 27.4	LFP; 300	LTO; 24	LFP; 362
Battery replacement [a]	8	8	8	8
FC power [kW]	85	-	83	-
FC replacement [a]	-	-	10	-
Charging strategy	-	Depot	-	Depot
Annual mileage [km/a]	58,000	58,000	94,000	94,000
Fuel consumption [kg/100km, kWh/100km]	6.4	151	6.7	125
H2 production method	Chlor-Alkali Electrolysis	-	Alkaline Electrolysis	
H2 infrastructure	Delivered over 320 km, compressed, trailer	-	Delivered over 316 km, compressed, trailer	
Bus price [€]	664,000	531,675	625,000	450,000
Specific maintenance cost [€/km]	0.88	0.88	0.88	0.88

(*continued*)

Table 1. (*continued*)

Parameter	Site 1 - FCB	Site 1 - BEB	Site 2 - FCB	Site 2 - BEB
Battery cost [€/kWh]	400	250	400	250
FC cost [€/kW]	1,000	-	1,000	-
Fuel price [€/kg H2, €/kWh]	6.8	0.18	7.0	0.21
Driver cost [€/h]	17.5	17.5	25	25
Infrastructure investment [€]	2,717,000	2,000,000	Included in H2 price	2,000,000
Annual infrastructure maintenance cost [€/a]	93,000	100,000	Included in H2 price	100,000
Number of buses infra-structure is designed for	40	60	20	60
Infrastructure lifetime [a]	20	12	15	12

2.4 Total Cost of Ownership Analysis

TCO analysis is a methodology to assess the life cycle costs of a product or service, considering all costs from investment through use up to disposal at the end of life. The TCO thus cover bus acquisition, maintenance costs including component replacement, driver costs, fuel costs, and allocated infrastructure costs (investment, regular maintenance, and potential credits for further use). To calculate the TCO, we use the Net Present Value (NPV) which represents the sum of the initial investment and the discounted payments throughout the life cycle. A general discount rate of 4% per year is assumed.

2.5 Operational Performance Assessment

FCBs and BEBs are compared regarding their operational performance, which generally cannot be expressed as a single value. Hence, the goal is rather to highlight conditions and preferences under which one of the bus systems shows advantages. Therefore, operational performance of FCBs and BEBs is discussed qualitatively and compared based on site information and information from previous projects.

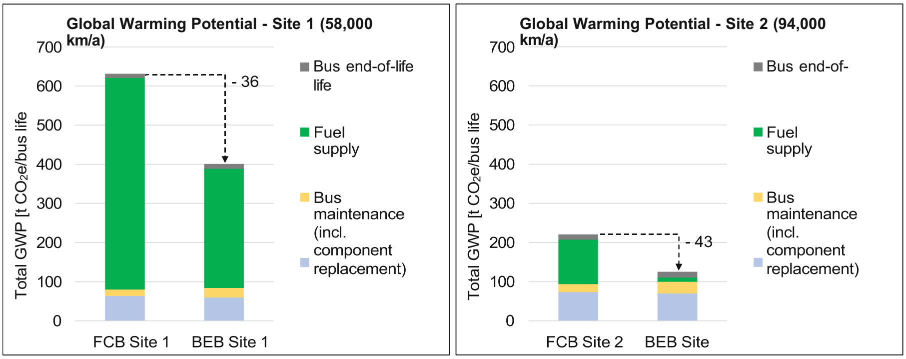

Fig. 1. Global Warming Potential for FCBs and BEBs at Site 1 and Site 2.

3 Results

3.1 Environmental Performance

Figure 1 displays the results of the CF calculation for the bus operation of both bus technologies at the two considered sites. At site 1, the total GWP of the FCB equals 631.4 t CO2e, while the GWP of the BEB amounts to 401.0 t CO2e and is thus 36% lower. At site 2, the total GWP associated with the FCB equals 220.5 t CO2e. With 125.1 t CO2e, the GWP of the BEB is around 43% lower. Conversion losses associated with hydrogen production and use are a fundamental advantage for BEBs in terms of climate impact.

Despite the higher mileage at site 2, the GWP is significantly lower than at site 1 due to the green electricity mix and the use of alkaline electrolysis for hydrogen production, respectively. The results emphasize that the energy origin significantly influences the CF of drivetrain technologies. Thus, while FCBs have a higher CF at both sites, FCBs at site 2 have a significantly lower CF than BEBs at site 1.

3.2 Economic Performance

Figure 2 shows the result of the TCO analysis for both sites. At site 1, the TCO of the FCBs amount to 2,074,000 €, and of the BEBs to 1,853,000 € or 11% lower. At site 2, the TCO equals 3,031,000 € for the FCBs and 2,272,000 € for the BEBs, thus 10% lower. The main reasons for the lower TCO of BEBs at both sites are the lower vehicle price and energy costs compared to FCBs. The high cost difference between the sites results from the considerably higher mileage at site 2, which is reflected in correspondingly higher maintenance, driver and fuel costs, also requiring an FC replacement after 10 years. However, with regard to the specific costs per kilometer, these are around 10% lower than those at site 1 due to the high mileage at site 2.

3.3 Operational Performance

Meeting operator's range requirements is a crucial factor for alternative bus drivetrains to fully replace diesel buses. At both considered JIVE sites, the BEBs are frequently

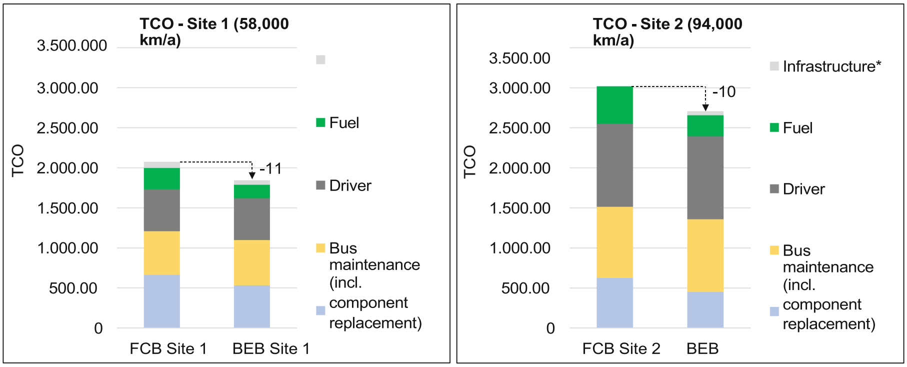

Fig. 2. Total Cost of Ownership for FCBs and BEBs at Site 1 and Site 2 (*For FCBs at site 2, hydrogen price includes infrastructure costs).

charged twice per day, while the FCBs are usually refueled only once. One operator stated that due to their lower range only approximately 80% of his routes could be serviced with BEBs. In addition, FCBs show a considerable advantage regarding the time needed for refueling and overall flexibility of deployment.

4 Discussion and Conclusion

Diesel buses no longer represent a technology to be considered in future decision making by Public Transport Operators (PTOs). Therefore, the comparison between FCBs and BEBs as two alternative drivetrain technologies is crucial. In terms of their environmental and economic performance, our results indicate an advantageousness of BEBs compared to FCBs.

Regarding climate impact, the use phase is decisive. Here, the lower CF of BEBs results from the lower primary energy demand as electricity is used directly instead of first being converted to hydrogen. However, in order to exploit the full GWP reduction potential of alternative drives, the use of renewable energy is absolutely necessary, as the comparison between the two sites in Fig. 1 shows.

Main reasons for the BEBs' cost advantage at both sites are the 20-30% lower vehicle price and around 40% lower energy costs. However, a cost comparison between both locations is not easily possible because the framework conditions differ considerably. This concerns especially mileage and energy consumption of the buses, infrastructure and energy costs, acquisition and maintenance costs for the vehicles, as well as the expected life time of vehicles and infrastructure.

The decisive advantage of FCBs is their greater flexibility due to their significantly higher range, which is often crucial for bus operation. In this work, all assessments were made assuming a 1:1 replacement, although the BEBs at both locations often have to be charged twice a day. If additional BEBs were required to meet operators' range requirements due to missing charging options, this would significantly alter or even reverse the results.

The choice of drive technology therefore depends on the operational requirements as well as the specific local conditions and resulting cost structure. The presented results are therefore limited to the considered cases and do not allow general statements regarding the advantageousness of a certain alternative drive technology.

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Requested policy to Support Market Transition – Experiences from a Swedish Electrified Logistics System Demonstrator

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Abstract. Swedish stakeholders have expressed their opinions in an interview study on the three most necessary, existing, or non-existing, policy and regulatory measures to accelerate the transition to emission-free electric freight transports with Heavy Duty Trucks (HDTs) in regional operation in Sweden. The study has been carried out as part of a Swedish system demonstration project, REEL, that includes more than 70 battery electric heavy-duty vehicles and associated charging infrastructure, operating various types of commercial goods flows together with 45 Swedish stakeholders, e.g., transport buyers, freight forwarders, hauliers, terminal and grid operators, OEMs, national authorities, and academic partners. In the study, 71% argue that one of the three most important policy measures is the public co-funding for truck investment to even out the TCO between electric and conventional trucks. 41% argue that the introduction of emission-free zones is a crucial policy measure. After the interview study, a follow-up work was carried out, in which a position paper was written together with the REEL actors. The position paper should be seen as a joint proposal from the REEL actors. Since many Swedish stakeholders argued that emission-free zones could be a crucial policy measure, and Sweden has yet to use that option, a study will be conducted to analyse and suggest how emission-free zones could be used in a Swedish context.

Keywords: battery-electric · demonstration · HDTs · policy · regulation · Heavy-duty

1 Introduction

Electric vehicles are considered an important technology to decarbonised road transport and meet stringent climate targets. The number of electric heavy-duty trucks (HDTs) on our roads is, however, still meagre (ICCT, 2023). To support increasing electrification of the freight sector several countries have implemented various policy instruments (Joelsson and Lantz, 2023). However, it is still uncertain which policy or combination of policies is most critical for facilitating the rapid adoption of electric HDTs.

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Sweden has implemented some measures to accelerate the transition's pace. In 2020, the Swedish government introduced a Climate Premium (Klimatpremien) as a purchase incentive for environmental vehicles, including electric trucks, to support introduction of new technology. The premium provides support of up to 20% of the vehicle's purchase price, or 40% of the additional cost compared to a corresponding diesel vehicle. Within the Climate Premium, the same support rate applies to all applicants regardless of company size, and applications are received and processed continuously. In addition to outright ownership, financial leasing is also approved, the type of leasing where the leasee takes over the vehicle at the end of the leasing period (Energimyndigheten, 2023).

At present, the Climate Premium is planned to continue until 2026. For the year 2021, 220 million Swedish kronor (MSEK) was allocated, and 345 MSEK for the year 2022; for 2023, the announced level is 345 MSEK per year. The Swedish government has also recently added increased resources to ensure that heavy electric-powered and other environmentally friendly trucks and non-road mobile machinery can be introduced to the market: 992 MSEK for 2024, 1493 MSEK for 2025 and 2023 MSEK for 2026 (Regeringen, 2023).

Support for electric heavy trucks can also be obtained in Sweden from the Climate Leap initiative (Klimatklivet). Within the Climate Leap, the support level can vary between 40–60% of the additional cost compared to a corresponding diesel vehicle, based on the size of the company applying for support. The Climate Leap accepts applications during limited periods, historically about three times a year, with an application time window of 2–3 weeks. The Climate Leap assesses possible support based on cost-effective emission reduction as well as profitability calculations, and the vehicle must be owned by the support recipient at the final report of the support. Grant of support is done in competition with other climate mitigation measures (Naturvårdsverket, 2023).

The Swedish purchase support scheme for HDTs is compared with other EU countries in Table 1 (TNO, 2022).

In addition to state funding of the vehicles, support for charging infrastructure is also available in Sweden. The Regional Electrification Pilots (REP) for Heavy Transport program aims to accelerate freight transport's electrification in Sweden. In 2022, the Swedish Energy Agency granted support for 140 public charging stations, 12 hydrogen refuelling stations, and one combined charging and hydrogen refuelling station from REP. In total, 1 400 MSEK were allocated. It is also possible to get grants from Climate Leap initiative (Klimatklivet) for both public and non-public charging infrastructure.

The project Regional Electrified Logistics (REEL) is a Swedish system demonstration, that was initiated in 2020, with aim to accelerate the transition towards transition to electrified emission-free regional heavy road freight transport. The project includes more than 70 battery-electric, mainly regional, HDTs, and associated charging infrastructure, operating various types of commercial goods flows together with 45 Swedish stakeholders, e.g., transport buyers, freight forwarders, haulers, terminal and grid operators, OEMs, national authorities, and academic partners.

To gain a more comprehensive understanding of potential effective policy measures, Swedish logistics companies, participating in the REEL project, have shared their insights. The study focused on identifying the top three existing or potential policy and

Table 1. Purchase support to HDTs in various EU countries (TNO, 2022)

	Heavy duty truck (urban)			Tractor and trailer (regional, long haul and construction)		
	Part of purchases	% pricedifference vs diesel	Funding cap €	Part of purchases	% price difference vs diesel	Funding cap €
Sweden	20%	40%		20%	40%	
Austria		80%			80%	
Germany		80%	350 000		80%	450 000
Italy			24 000			24 000
The Netherlands		45%	84 000		45%	131 900
Poland	30%		43 280	30%		43 280
Spain			145 000			160 000
UK	20%		29 310	20%		29 310
France		40%	50 000		40%	50 000

regulatory measures deemed most crucial for accelerating the transition to zero-emission heavy-duty vehicles in regional operations.

Moreover, within the project, joint efforts have also been undertaken to develop a position paper on prioritised actions and the design of support systems.

Since many Swedish logistics companies argued that emission-free zones could be a crucial policy measure and Sweden has yet to use that policy option, a study will be carried out to analyse and suggest how emission-free zones could be used in a Swedish context. Swedish municipalities can implement emission-free zones already, but no city has done it yet. With current regulations it is also impossible to separate between cars and HDTs, so it is challenging to have an emission-free zone only for HDTs in a Swedish city.

2 Method

An interview study has been carried out as part of the REEL project. The interviews with logistics companies participating in the project were performed by the project's trustee representatives between April 2022 and October 2022. The interviews were semi-structured, encouraging the interviewees to elaborate on the specific question to capture several perspectives rather than obtain a definitive answer. In total, 18 organisations have been interviewed in the study. Interviewees were representatives of the participating logistics companies in REEL possessing roles such as fleet manager, logistics manager, sustainability manager, transport manager.

After the interview study, a follow-up work was carried out, in which a position paper was written together with the REEL actors. The position paper should be seen as a joint proposal from the REEL actors on what Swedish authorities should do regarding procurement support and the design of the administration of the support systems. The position paper was later submitted to the government as a proposal for priorities.

3 Results from the Interview Study

The results of the policy-related questions of the interview study highlight the top three existing or potential policy and regulatory measures deemed most crucial for accelerating the transition to zero-emission HDTs in regional operations. And the actors' response was:

71% argue that one of the three most important policy measures is the public co-funding for truck investment to even out the Total Cost of Ownership (TCO) between electric and conventional trucks. Concerning this measure, they also raise the importance of minimising administration and to have a predictability and long-term perspective in the incentive schemes.

53% argue that one of the three most important policy measures for regional electric routes is the public co-funding for investment in non-public and/or semi-public charging infrastructure. Actors find that today's incentive schemes are too centred towards public charging and would prefer a change of focus to enable more charging at own and/or goods senders'/receivers' premises while reloading goods, etc.

41% argue that introduction of emission-free zones is a crucial policy measure. This is considered to have the possibility to create an entirely different demand for electric vehicles and competition on equal terms. When introducing zones, it must be communicated well in advance and with clarity, and to work as intended it requires support from law enforcement.

Public co-funding for investments in HDTs and charging infrastructure are currently the most common economic policy in several countries to promote electric HDT deployment, as also shown in a policy outlook carried out within the REEL project. However, a few countries will also be implementing emission-free zones (Joelsson and Lantz, 2023).

4 Results from Position Paper

The results from collaborative work after the interview study resulted in a position paper with more detailed recommendations. The actors in the REEL project want to see the following development of the current incentive system.

Long-Term Stability and Predictability

The major system shift that the actors are facing is not only costly in terms of investments in new vehicles and charging infrastructure, but it also means that logistics operators must learn how to best manage the new conditions. The sales process with customers and suppliers to jointly make the investment decision in a new system with electric trucks and charging infrastructure is also long, which requires lasting conditions from the state so that the terms do not suddenly change.

Support for Vehicles

For all transport companies, cost-neutral TCO compared to fossil-fuelled trucks is crucial for how quickly the transition to climate-neutral transportation can be made. Therefore, the actors in the REEL project support that an increase in the current support level would be justified to further accelerate the transition. Data from REEL actors shows that an electric truck in urban operation today costs approximately 15% more in total cost per kilometre without investment support. In urban traffic the annual distances driven are relatively short, and thus the investment in the vehicle represents the largest cost in the transport companies' cost calculations. An electric truck in heavier regional operation today costs approximately 12% more in total cost per kilometre without investment support. Therefor investment support is still needed.

Increase Opportunities for Support for Charging Infrastructure

In addition to support for vehicles, support for charging infrastructure is also needed. The most important part of the charging infrastructure for urban and regional transport is the non-public sector, such as depots, logistics terminals, and at goods receiving points. This will be the base where most of the energy will be charged. Being able to charge vehicles at a natural stop, for example at customers during unloading and loading, supports good transport efficiency and allows transporters to maintain their quality. Alongside depot charging and destination charging, public charging is also needed.

In addition to maintained and improved investment support, which is the highest priority for the stakeholders, other prioritised proposals for regulatory changes have emerged in the process of writing the position paper:

Emission-Free Zones – The introduction of emission-free zones in cities for utility vehicles is believed to have the potential to significantly accelerate the transformation and create competition on equal terms. When implementing emission-free zones, it should be communicated well in advance and clearly, and to function as intended, the authorities must ensure compliance by all.

Night Deliveries in Cities – Increase opportunities for night deliveries in city centres with electric vehicles, by imposing requirements on municipalities, property owners, and goods recipients. Night deliveries could enable better utilisation of vehicles and more efficient deliveries.

Driving and Rest Time – These rules should be more flexible during a transition period until a sufficient charging network is established. It also needs to be clarified that breaks count as rest, even though charging takes place simultaneously.

Kilometre and Congestion Tax – Electric HDTs could have lower congestion taxes compared to conventional vehicles, and furthermore, when implementing a kilometre tax, differentiated fees that benefit electric trucks should be applied, like in Germany.

5 Study About Emission-Free Zones in Sweden

Emission-free zones have, as previously mentioned, been identified by Swedish stakeholders as one of the most promising policy instruments to favour the introduction of electric trucks. Although there are several examples of emission free zones or ultra-low emission zones in Europe and elsewhere there are no such zones in Sweden today.

An ongoing study is therefore analysing how such zones could be implemented and monitored in Sweden and what effects such zones could have on the local and regional truck fleet. The study includes an overview of current Swedish and international regulations as well as case studies. These case studies focus on how trucks move in the city, how many trucks that would be affected depending on the design of the emission-free zone. The outcome of the study includes a quantitative assessment of the impact such zones could have as well recommendations for policy makers.

6 Conclusion

Support for the purchase of electric trucks and charging infrastructure are the decisive policy measures, according to experiences from the 45 major Swedish actors who have come together in one of Europe's largest initiatives, the REEL project, to accelerate the transition to electric HDTs. The support exists, but it should be developed to have long-term stability and predictability. Moreover, regulatory incentives related to access both in time and place, such as permitting nighttime delivery and introducing emission free zones, are highlighted as promising policies to enhance the demand for electric HDTs.

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Shift to Low/Zero Emission Trucks: Research into Logistics Issues in the Hungarian Road Transport Sector

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Abstract. In 2017, road transport in the EU accounted for 93% of the total energy consumption of inland transportation. 94% of this consumption was based on fossil fuels. Europe aims to achieve climate neutrality by 2050 by reducing greenhouse gas emissions. This research aims to examine the possible scenarios to support the spread of using alternative fuel trucks including electrification by the wider range of hauliers in Hungary by analyzing the suggestions and applied best practices. Any solution to be applicable requires modifications to suit other countries; therefore, we present the role of supply/demand on the national market and transport policies in an international context. We also describe the characteristics of the available technologies and their challenges. Trucks use rest areas differently in time and location. Therefore, we examined driving patterns and rest periods based on the GPS data of the trucks and concluded with the charging infrastructure in Hungary also, from the point of view of integration into the European network, especially near the border crossings to avoid an oversupply of border charging points.

Keywords: Trucks Electrification · Alternative Fuel · Logistics · Freight Transport · Charging Infrastructure

1 Introduction

With the accelerating climate crisis and the massive increase in greenhouse gas emissions, many efforts have been directed to reduce these emissions and control their negative environmental effects. The transportation sector is one of the main players in this regard. It accounts for almost 16% of greenhouse gas emissions. Road freight accounts for about a third of these emissions [1]. It represented 75.3% of the total inland freight transport in the EU during 2018 [2]. Road transport in the EU accounted for 31.7% of the total energy consumption [3]; 94% of this consumption was based on fossil fuels [4]. Although the EU has not succeeded in reducing greenhouse gas emissions by 6% in 2020 compared to 2010 and has only decreased it by 5.5%, The European Green Deal

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promises a 90% reduction in transport emissions by 2050 [5]. In this regard, several projects and programs have been suggested to reduce transport emissions in Europe and in other countries around the world like the white paper in 2011 [6], the mobility strategy of the European Commission for green mobility [7], and the CIVITAS initiatives for sustainable and smart urban mobility [8]. The decarbonization of transport initiatives by the International Transport Forum (ITF) was also one of the suggested programs on a global level [9]. However, road freight transport has been accelerating more than road passenger transport, in the EU between 2000 and 2019 the rate of its growth was 31% [10]. Trucks are responsible for one-fifth of the transport sector's emissions in Europe [11]. This has encouraged us to proceed in our research to examine the possible scenarios to support the spread of using alternative fuel trucks including electrification by a wider range of hauliers in Hungary.

2 Alternative Fuel Trucks and Alternative Powertrains

Several solutions and scenarios have been suggested to reduce transport emissions and move towards sustainability. These solutions include vehicle electrification through batteries or electric road systems and the use of hydrogen fuel cells. Some solutions also focus on hybrid powertrains and low-carbon fuels, like biofuels, hydrogen, and diesel electrofuels [11]. On the other hand, improving aerodynamics, reducing tyres' resistance, reducing vehicle weight, improving eco-driving, and alleviating restrictions on the truck length and weight are also included in the suggested solutions for improvement [12]. The applied and planned scenarios were different in each country. The green freight program in Canada for example, was launched to achieve fleet energy assessments, fleet retrofits, engine repowers, logistical best-practice implementation, and the purchase of low-carbon vehicles [13]. New Zealand suggested alternative green fuels [14], while Germany and France focused on electric road systems [15]. Norway introduced generous tax incentives to promote zero-emission vehicles, including exemptions from registration taxes, motor fuel taxes, road, and parking taxes. [16]. The initiatives of the Hungarian national energy strategy aim to improve carbon-free solar and nuclear power capacities. Given the country's size and concentrated economic activities, the feasible solution for zero-emission vehicles appears to be the electric powertrain, with a possible integration of hydrogen in the future.

3 Trucks Electrification: Challenges and Barriers

Replacing the current dependency on diesel fuels for road trucks and moving towards more electrification to achieve the goal of carbon neutrality could face many challenges. The main challenge for electrification through batteries is the size and weight of the battery and the charging network [11]. The availability of charging stations for long-haul routes is sometimes an obstacle [12]. On the one hand, the lower power density of batteries compared to diesel fuel limits the range of the vehicle and the payload. On the other hand, charging the batteries requires a longer time or an expensive infrastructure to provide fast charging [1]. Three methods could be provided for charging; plug-in cable charging or wireless charging where the vehicles should stay at the station for the whole charging time, and battery swapping where the batteries could be charged before swapping (however, the size of the batteries of the trucks will not likely make it feasible). Providing the needed infrastructure for reaching the goal could be a challenging task. The European supplier of battery-charging infrastructure “Allego” suggested having 11 stations along TEN-T every 75–100 km with at least 20 chargers with 450 kW DC power outlet [17]. In a study conducted by Fraunhofer ISI based on GPS data of the truck manufacturers (of 400.000 trucks in operation all over Europe), it is concluded that all European countries should equip their top 10% of truck-frequented rest areas with truck-accessible chargers by 2027 (3.126 in Europe and in Hungary 59 specifically) [18]. In a case study from Switzerland, it was found that full electrification increased the total Swiss electricity demand by about 5% but it is possible and requires some modifications in the regulations like the maximum permissible weight [19]. In the case of Finland, the use of batteries was not possible as in the case of Switzerland due to the implementation of long and heavy truck-trailer combinations. This made the electrification through the transport road system much better for Finland [20]. We can say that truck electrification is different in each country depending on its situation. However, none of the techniques of electrification will be effective for the decarbonization process if the source of the power is not clean [12].

4 Characterization of Freight Transport Demand in Hungary

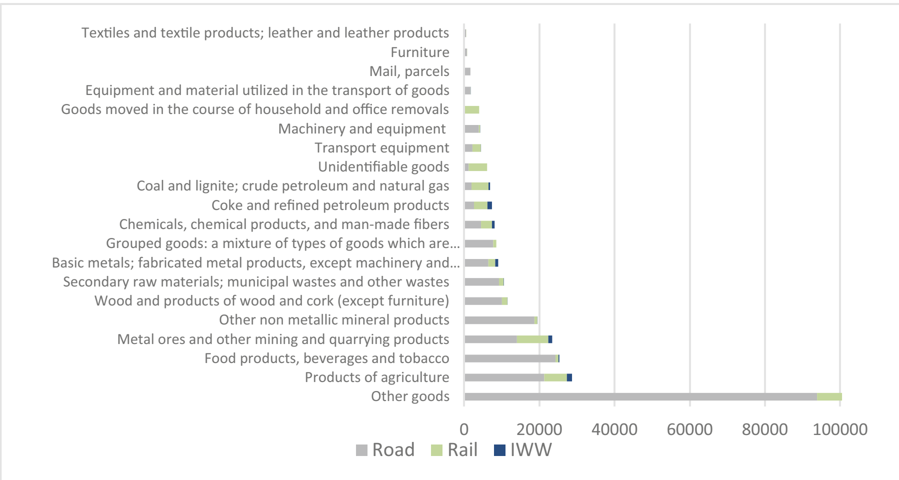

Fig. 1. Distribution of goods by transport mode (tons) in Hungary in 2022 – source: own editing based on Eurostat data.

Hungary’s main commercial destinations are primarily European countries (88%). The data from the “Trading Economics” website showed that until 2022, the largest export partner for Hungary was Germany (25%). Italy, Romania, Slovakia, Austria, Poland, France, and the Czech Republic respectively had a big share as export partners for Hungary as well. Germany also represented the largest import partner for Hungary until 2022 (21%). Austria, China, Slovakia, Russia, Poland, Netherlands, the Czech Republic, and Italy had a big share as import partners for Hungary as well. It was found that road transport was the dominant mode for all goods except heavy raw materials like coal, petroleum, and natural gas, and the group of vehicles to be transported for demolition waste and repairs, where rail is the preferred mode of transport. The role of water transport was marginal for all types of goods. Detailed information is required for planning fleet and charging infrastructure development to electrify road freight transport and shift long-haul demand to rail and waterway (as can be seen in Fig. 1 - non-specific). eFTI regulation will provide detailed information about freight demand, essential for designing the complex electric fleet ecosystem.

5 Trucks Driving Patterns and Electric Charging Infrastructure

In the conducted research by Csendes et al. to calculate the driving and resting time of truck drivers in Hungary, it was found that rest periods are concentrated between 0 to 1.5 h and 8 to 10 h. No correlation was found between the length of driving and resting periods. Drivers might stop for a long rest after a short driving period or the other way round (see Fig. 2). The highest number of parked trucks was between 10 am and 03 pm [21].

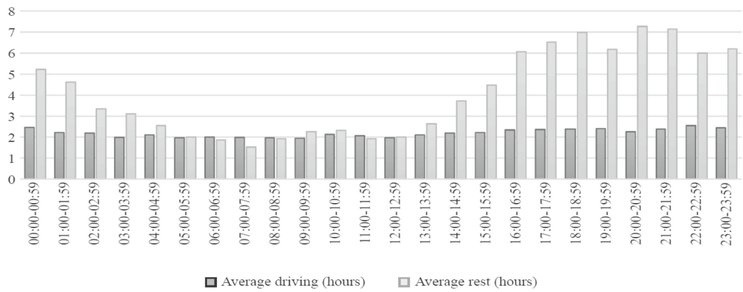

Fig. 2. Average length of truck drivers' driving and rest periods – source: Csendes et al., 2021

To investigate if the planned charging infrastructure could support the efforts of truck electrification, it is also important to analyze the suggested network by defining the distances between every two adjacent charging points (as they are not suggested to be established evenly distributed on the road infrastructure but based on truck stop frequency) taking into consideration their capacities (see Fig. 3). Considering the road freight network and the planned locations of charging points we can conclude that the density around the TEN-T border crossing points will certainly be utilized at a higher rate if the development of these electric charging points happens in time, soon. Otherwise, if the neighboring countries invest more and faster in developing their charging network, there will be an imbalance that can decrease the feasibility of first -and last-mile logistics activities around border crossings in Hungary.

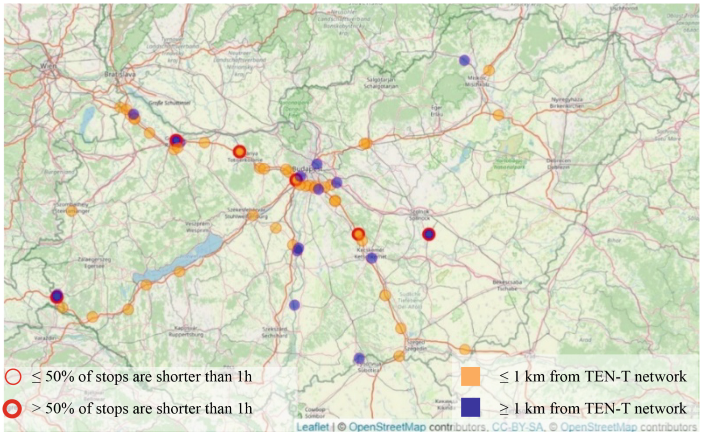

Fig. 3. Necessary charging infrastructure in Hungary: Top 10% most frequent locations – source: ACEA: Interactive maps – Electric trucks: stop locations, Central Europe.

6 Conclusion

When planning charging infrastructure for Hungarian trucks, commercial relations should be considered. Our economy is closely connected with Western Europe, concerning both import and export activities. Deriving from the most frequented resting locations results in a dispersion of charging points gravitating towards the northwest. However, route planning and driving patterns may be different: route planning is based on the regulation of professional drivers' theoretically driven maximum period (for cost efficiency purposes), while in practice we have seen the scheduling and length of driven and resting periods diverge significantly from the frame defined by the rules. To support transport safety (avoid personnel fatigue), seamless flow of (electric) commercial vehicles, and the balance of the electric energy supply network, more detailed research is needed, for achieving a reservation/scheduling platform for place and time of charging (to deflate peak hour demand). However, switching to electric or hydrogen trucks will not solve all freight demand challenges. Freight transport faces issues such as congestion, delays, under-utilization of capacities, and lack of infrastructure for shifting to rail. We need to consider the solutions recommended by the concept of the Physical Internet [22]. Improving railway and inland waterway transport infrastructure is a long-term process in Central-Eastern Europe. However, quick action is necessary to achieve climate goals and improve road transport efficiency. In our further research, we plan to study the impact of introducing the (semi-) automated „platooning service system" of battery electric trucks in our country on the transport, logistics, and electricity system infrastructure to achieve synergistic effects.

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Tracking Progress Towards Net Zero Mobility: A Concept for a Mobility Transition Index

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Abstract. This status paper presents an initial conceptual framework to develop a novel sustainable and electric mobility index to measure progress towards sustainable and low-carbon surface transport and assess the readiness and capacity of cities and countries to achieve a net-zero transition. The proposed index is based on a multi-layered approach, encompassing different sub-indices, capturing the different surface transport modes (rail, inland water, road transport) and types (public, private and informal), and considering the state of data in the target regions. The index aims to provide a comprehensive overview of the transition to low-emission mobility across surface transport modes and enable governments in low and middle-income countries (LMICs), where a limited overview of the capabilities and progress in decarbonising surface transport exists, to identify critical barriers to decarbonising their transport systems.

Keywords: Net-Zero · Sustainable Mobility · Electric Mobility · Key Performance Indicators

1 Introduction

Cities and countries are working on the challenging quest to decarbonise transport systems and provide sustainable mobility solutions for all. Tracking progress and knowledge sharing can be a powerful enabler in identifying viable solutions for an integrated mix of transport modes, including public transport, mass transit, new and shared mobility services, informal transport, walking and cycling, all of which will be needed to move towards zero-emission mobility. There is much guidance and advice on low- and zero-emission technologies, infrastructures and services. However, the link between individual technologies, policies and investments with the overall transition pathway is often missing. Providing an international platform, guidance, and comparative indices can contribute towards developing or identifying decarbonising pathways.

An index is created by aggregating individual indicators using simple or advanced statistical methods to measure complex or multidimensional phenomena, typically resulting from combining several sub-indicators [1, 2]. A key advantage of using indices in transportation is their simplicity. Indices can summarise complex issues in a single,

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easy-to-understand snapshot, promoting effective communication among researchers, scientists, policymakers, the public, and decision-makers [3, 4].

This status paper aims to initiate a process to develop a sustainable and electric mobility index in low and middle-income countries (LMICs). The envisaged index provides a comprehensive overview of the transition to low-emission mobility across surface transport modes. It enables decision-makers to identify critical barriers and potentials to decarbonising their transport systems.

2 Literature Review

[2] describes indicators as a crucial informational tool for sustainable planning and delivering transport. Indicators are used in various applications for planning, decision support and operational tasks as tools to describe, forecast, review, diagnose, decide, account, learn and communicate. Each of these characteristics of the indicators allows the user to understand, assess, explain, predict and identify the various facets that guide the transition to low-emission mobility systems [2].

A bibliometric analysis on the Web of Science (WoS) platform was conducted to obtain a preliminary overview of the vast scientific landscape around composite indicators in the field of sustainable surface transport. The bibliometric analysis was done using the software package “Bibliometrix” in R [5]. With the defined search strategy, a total of 568 results were retrieved. After a thorough review, articles unrelated to surface transport were excluded, and duplicate entries were removed, leading to 497 articles.

Scientific production increased from one publication in 2004 to 95 in 2023. Based on the location of the first author, regional productivity is assessed. Most publications are from East Asia and the Pacific, with 179 in total. Meanwhile, South Asia and sub-Saharan Africa are catching up with 36 and 11 publications, respectively (Fig. 1).

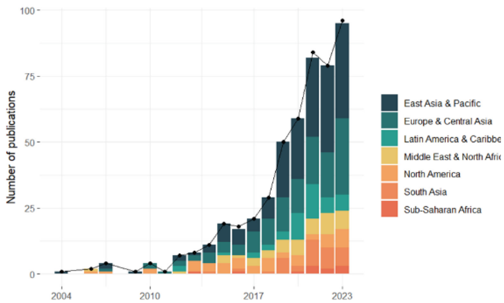

Fig. 1. Scientific production (Source: Own depiction based on WoS 2024)

Figure 2 depicts a network visualisation that identifies three distinct clusters of keywords in the literature based on their frequency of co-occurrence. The first cluster includes terms related to performance, management, and decision-making. The second cluster is centred around energy consumption, efficiency, and CO2 emissions, while the third cluster revolves around behaviour, walkability, health, accessibility, and land use. These clusters reveal dominant themes and frequently analysed issues concerning indices in the context of sustainable transport.

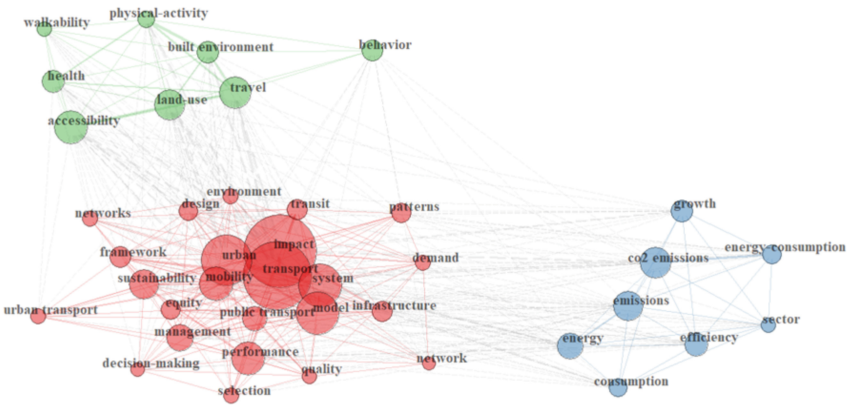

Fig. 2. Keyword co-occurrences (Source: Own depiction based on WoS 2023 using Bibliometrix in R)

3 Approaches to Constructing Composite Indicators

Comprehensive guidelines, such as those developed by [1] and [3], provide concise instructions for index development. Among others, these highlight the importance of ensuring that indices are not only relevant, reliable and methodologically sound, but also comparable and easily accessible to relevant stakeholders. [4] emphasises the importance of several key steps based on analysing 24 sustainable transport indices and academic literature to develop a robust and reliable sustainable transport index. Eight (8) steps generally used for the development of sustainable transport indices were identified: 1) setting objectives, 2) selecting an appropriate framework, 3) investigating and defining determinants, and 4) developing a set of sustainable transport indicators before 5) normalising, 6) weighting and 7) aggregating the selected indicators. Finally, step 8) involves applying the developed index to assess transport systems [4].

To establish a robust framework that effectively promotes sustainability in transportation, [2] cite seven essential criteria that any framework, regardless of its type, should meet. Frameworks need to be 1) comprehensive, 2) connected to overall objectives and goals, 3) internally integrated, 4) able to capture effects of variable interactions, 5) ensuring stakeholder's perspectives are reflected, 6) capabilities and constraints are considered, and 7) be flexible and foster self-learning to enable suitability in rapidly changing contexts.

Organising information requires a framework with an overarching goal and internal structure of indicators [2]. It is important to consider three essential dimensions to create an effective and practical framework:

1. **Substance** refers to elements that need to be measured by describing the core goals the index aims to capture.

2. **Intention** addresses the reasoning and purpose of the index, including the level of activity addressed and its application.
3. **Procedure** covers the process involved in identifying, creating, and reporting the dimensions and individual indicators.

4 A Conceptual Framework for an Index

While each step is important in developing an index, this status paper focuses on setting objectives and selecting an appropriate framework, which serve as foundational pillars for all subsequent steps. The aim is to establish a solid foundation, promote stakeholder engagement, ensure indicator relevance, increase transparency, and foster value creation in the development process.

4.1 Substance

Sustainability Concepts: The index helps LMICs decarbonise surface transport via a toolkit that diagnoses the state of decarbonisation and identifies pathways to achieve net-zero emissions by 2050 while ensuring accessibility and affordability of mobility. It also considers policy, capacity, gender, equity, inclusion, and just transition.

Transport System Boundary: The index will cover all surface transportation modes, including private and public transport, mass transit, new and shared mobility services, informal transport, walking, and cycling. Capturing nuances and complexities of various forms of surface transportation, especially informal transport used in LMICs, will be reflected in the index development and application.

4.2 Intention

The purpose of the index is to allow LMICs to find the optimal pathway to decarbonise the mobility sector. To achieve this goal, the index must relate to the current targets at an urban and national level and be coupled with the actual mobility situation at the time of measurement. Obtaining these data allows the development of forecasts and trajectories as a subsequent activity to the index development.

4.3 Procedure

Dimensions and Types of Indicators: Based on the substance and intention defined above, preliminary core components and indicators for the index based on existing best practices and development pathways have been developed. The preliminary index dimensions are outlined in Table 2.

Systematically capturing dimensions and selected variables with sufficient details for the different surface transport types and modes will highlight the main gaps and opportunities for acting. Additionally, potential indicators will be evaluated regarding their availability, quality, quantity and relevance of existing data.

Indicator Connectivity to Tools and Institutionalisation: To attain the envisaged result of an index it is essential that the index is widely available and user-friendly. Tools designed using spreadsheets, accompanied by a methodological handbook and tailored for a country with default values for certain indicators is essential. The index for LMICs aims to address these factors and through rigorous stakeholder consultation the user-friendliness in identifying and populating data is ensured. In regions, where existing efforts to collate data are present e.g. the Asia Transport Outlook (ATO), will support the index in identifying default values for certain indicators. We also reckon that similar efforts such as the ATO will be beneficial for the African region where data availability is challenging. Our proposed index will strive to support efforts such as ATO. This contribution will be mutually beneficial as it supports the broad transparency and accountability elements that all indices aspire (Table 1).

Table 1. Potential factors expressing the intention of the index

Aspect	Description
Time orientation	Current and past trajectories
Level of activity	Development status, transport system characteristics
Stage in decision making	Support LMICs to better understand which measures can be most efficient, considering their circumstances and enable measuring and verifying surface transport decarbonisation
Indicator applications	Describe and review a country's transport performance towards achieving net zero by 2050, allow comparison with other countries and track progress over the years

Table 2. Potential dimensions that can support identifying the indicators in an index

Index Dimension	Description
Net-zero emissions	The net-zero emission dimension measures a country's progress in reducing carbon from surface transport. Subdimensions include transport activity, structure/modal share, energy/carbon intensities, electricity system readiness, and factors driving energy source emissions
Decarbonisation Policy and Governance	Captures priority gaps in decarbonising surface transportation policies. It can also include mechanisms to examine how decarbonisation policies integrate with other dimensions like gender, equity, and inclusion

(*continued*)

Table 2. (*continued*)

Index Dimension	Description
Decarbonisation Capacities and Resources	Include indicators for resource allocation and capacity of countries transitioning to surface transport decarbonisation in the toolkit. Possible subdimensions include adoption of low-carbon technologies, innovation activity and investment in research and development
Transition Readiness	This includes evaluating transportation availability, accessibility, affordability, and acceptability. These factors are essential for inducing a shift towards transport decarbonisation

5 Conclusion

This status paper proposes a multi-layered index integrating various dimensions and modes of land transport, covering rail, road, and inland waterways and public, private, and informal modes.

Based on the approach mentioned in this paper, we will include stakeholders during index development and consider the data situation in the target regions. The future index development will include formulating a methodology, assessing existing indices, validating with a case study involving LMICs and stakeholders, confirming indicators, and assessing data availability. The index will be revised iteratively to ensure it is robust and applicable, providing a reliable tool for developing sustainable transport models.

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Optimized Electrified Meeting-Point-Based Feeder Bus Services with Capacitated Charging Stations and Partial Recharges

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Abstract. Meeting-point-based feeder services using EVs have good potential to achieve an efficient and clean on-demand mobility service. However, customer-to-meeting-point, vehicle routing, and charging scheduling need to be jointly optimized to achieve the best system performance. To this aim, we assess the effect of different system parameters and configure them based on our previously developed hybrid metaheuristic algorithm. A set of test instances based on morning peak hour commuting scenarios between the cities of Arlon and Luxembourg are used to evaluate the impact of the set parameters on the optimal solutions. The experimental results suggest that higher meeting point availability can achieve better system performance. By jointly configuring different system parameters, the overall system performance can be significantly improved (−10.8% total kilometers traveled by vehicles compared to the benchmark) to serve all requests. Our experimental results show that the meeting-point-based system can reduce up to 70.2% the fleet size, 6.4% the in-vehicle travel time and 49.4% the kilometers traveled when compared to a traditional door-to-door dial-a-ride system.

Keywords: Demand responsive transport · Meeting point · Electric vehicle · Synchronization constraint · Mixed integer linear programming · Metaheuristic

1 Introduction

The climate crisis urges electrification in the transportation sector, including demand-responsive transportation (DRT) systems which introduce additional constraints regarding electric charging operations. Besides, the "meeting-point (MP)-based strategy", which utilizes the nearby pickup/drop-off locations to the customers' final origin/destination, has increasingly been studied and applied to improve the efficiency of DRT by reducing the operational costs with little inconvenience to customers (Czioska et al. 2019; Ma et al. 2021). Despite its benefit, the integration of an MP-based strategy into an electrified DRT system complicates vehicle dispatching and routing operations

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due to the interactions between customer-to-meeting point assignment, vehicle routing, and charging scheduling. Existing studies often assume unlimited charging station capacity, usually violated in practice because the availability of (fast-)charging infrastructure is very limited due to high investment costs. While electric vehicle routing problems have been studied extensively, efficient solution algorithms for solving medium/large problem instances considering capacity-constrained charging stations are still underdeveloped.

To fill those gaps, our previous study (Ma et al. 2023a,b) proposed a model for meeting-point-based electric feeder service with charging synchronization constraints (MP-EFCS), where the service radius of meeting points is a system parameter to trade off user's inconvenience (walking time) and operational costs (vehicle routing time and charging time). The developed method allows the system to jointly optimize the customer-to-meeting-point assignment and vehicle routing costs under vehicle charging synchronization constraints with partial recharges. The problem is a variant of dial-a-ride problems (Cordeau 2006) with EVs, but is more complex due to the charging synchronization constraints. Unlike traditional door-to-door DRT, in the MP-EFCS, customers are assigned to the one of predefined meeting points within a given maximum walking distance. Vehicles pick up customers at these meeting points and drop them off at their desired transit stations within desired arrival time windows.

Using a larger meeting point separation distance may reduce the number of customers due to the longer walking distance. In addition, when other system parameters are considered (i.e. fleet size, different weights used in the objective function, etc.), there might be synergies to optimize the system performance. However, these aspects have not been studied yet. Therefore, in this study, we provide new contributions to analyze the effect of different system parameters and configure the system parameters of MP-EFCS service in a study area. The main contributions are as follows.

- We analyze the impact of various system parameters of the MP-EFCS service, including fleet size, meeting point separation distance, and user-defined coefficients in the objective functions.
- Based on the identified key system parameters, we optimize their configuration to minimize the operator's cost with the least impact on customer inconvenience.
- The computational experiments are performed for a morning peak-hour commuting scenario from Arlon to Luxembourg. The key performance indicators are analyzed to evaluate the performance of the MP-EFCS service. Its performance is compared with traditional dial-a-ride service.

2 Related Work

Demand-responsive transport (DRT) services have been studied and implemented since the seventies (Wilson et al. 1976). Extensive research has been conducted on this topic during the last half-century. The reader is referred to the recent works of Vansteenwegen et al. (2022) and Ma and Fang (2022) for a comprehensive review. In this section, we briefly review the meeting-point-based approach to improve the efficiency of classical door-to-door DRT and the methodology to configure the fleet size and the system parameters of DRT services.

The meeting-point-based DRT services consist of operating vehicle routes on a set of predefined "meeting points", i.e., street corners, existing bus stops, or parking lots near the customer's origin or destination (Czioska et al. 2019). This approach has been studied for ridesharing services to allow for reducing vehicle routing costs to match the origins and destinations of drivers and riders (Stiglic et al. 2015). Similar concepts have been studied to reduce the operating costs of door-to-door DRT services. For example, Montenegro et al. (2022) propose a flexible feeder service in which a fleet of buses operates on a set of mandatory bus stops on a backbone line while allowing flexible bus routes to visit optional bus stops in the service area. The authors formulate the problem as a MILP and develop a large neighborhood search algorithm to solve it for large test instances (Montenegro et al. 2021). The analytical approach has been developed in the past for this type of flexible bus service (Chang and Schonfeld 1991). A similar on-demand bus system is proposed by Melis and Sörensen (2022). The authors develop a MILP model to assign customer requests to bus stops in the first stage and then optimize bus routes in the second stage to minimize the total user ride time. An efficient large neighborhood search heuristic is developed to solve large test instances. The results show that the total user ride time is lower for on-demand bus systems compared to fixed-route bus services.

The fleet size and mix vehicle routing problem consists of determining the vehicle routing, type, and number of vehicles to serve a set of customer demands at minimum cost (Brandão 2009). The problem can be formulated as a MILP with vehicle type-specific operating constraints. Since the problem is NP-hard, many heuristic and metaheuristic approaches have been developed (Hiermann et al. 2016). Hiermann et al. (2016) added different types of EVs to the problem, aiming to reduce both vehicle purchasing and routing costs. Other studies used an agent-based simulation approach for fleet size minimization considering stochastic demand (Scheltes and Correia 2017). These studies focus on minimizing the total system cost by considering fleet utilization, maintenance, insurance, and/or depreciation costs. However, to achieve optimal system performance, other key system parameters need to be jointly configured. For electric vehicle routing problems with capacitated charging stations, the reader is referred to Lam et al. (2022) and Ma et al. (2023b) for related literature reviews.

The main distinguishing features of the MP-EFCS service in this study are that it is a more flexible meeting-point-based service and allows customers to be rejected. In this way, the system is more flexible and cost-efficient. For customer inconvenience, constraints related to maximum walking distance, maximum user riding time, and time window constraints at drop-off transit stations are considered. In addition, the system is operated with a fleet of EVs, and their charging operations are optimized with partial recharge policy and charging synchronization constraints.

3 Methodology

3.1 Problem Description

Consider a meeting-point-based electric (first-mile) feeder service using a fleet of electric vehicles (or buses interchangeably) in a rural area. Customers are assumed to be willing to walk to meeting points within a maximum walking distance. Customers submit travel requests a day ahead via a dedicated platform detailing their origin, drop-off transit stations, and desired arrival time at transit stations which corresponds to the transit departure time. Based on the collected requests, the operator confirms requests, their pick-up time, and recommended meeting points or reject requests. Vehicles must reach the transit stations within a pre-defined buffer time (i.e., 10 min) before the departure of trains (transit service). Vehicles' charge levels have maximum and minimum bounds, with charging done at limited operator-owned chargers. The charging speed is assumed linear. Charging operations cannot overlap at any charger. The objective of the MP-EFCS service is to minimize the system costs. Four groups of constraints are considered as follows.

- **Customer-to-meeting-point assignment constraints**: Assign each customer to one meeting point within their maximum walking distance.
- **Vehicle routing constraints**: Ensure that the vehicle capacity is respected and that the vehicle arrival time and starting time of service at each node are consistent, given the associated time window and ride time constraints.
- **Energy constraints**: Specify the state of charge of vehicles at each node when traversing arcs and when performing charging operations.
- **Charging scheduling (synchronization) constraints**: Prevent simultaneous charging at any single charger

The MILP formulation of the MP-EFCS is as follows (Ma et al. 2023a).

$$MinZ = \lambda_1 \sum\nolimits_{k \in K} \left(\sum\nolimits_{(i,j) \in \mathcal{A}_B} t_{ij} x_{ij}^k + \sum\nolimits_{s \in S'} \tau_s^k \right) + \lambda_2 \sum_{(r,i) \in \mathcal{A}_c} \sum_{k \in K} y_{ri}^k t_{ri}$$
$$+ \lambda_3 \sum_{k \in K} \sum_{i \in D'} W_i^k + \lambda_4 \sum\nolimits_{(r,i) \in \mathcal{A}_c} \left((1 - \sum_{k \in K} y_{ri}^k \right) \tag{1}$$

The objective function (1) seeks to minimize the weighted sum of vehicle travel time (t_{ij}) and charging time (τ_s^k) (first term), customer walking time (t_{ri}) (second term), excess vehicle waiting time at transit stations (W_i^k) (third term), and the penalty for unserved customers (fourth term). λ_1 to λ_3 are user-defined weights to account for the tradeoffs between operational costs and customer incontinence. λ_4 is the penalty for rejecting customers. The notation is shown in Appendix A.

Customer-to-meeting-point assignment constraints:

$$\sum_{k \in K} \sum_{i \in G'} y_{ri}^k \leq 1, \quad \forall r \in R \tag{2}$$

$$\sum_{k \in K} \sum\nolimits_{i \in G'} w_{ri} y_{ri}^k \leq w_{max}, \quad \forall r \in R \tag{3}$$

Vehicle routing constraints:

$$\sum\nolimits_{j \in G' \cup S' \cup \{N+1\}} x_{0j}^k = 1, \quad \forall k \in K \tag{4}$$

$$\sum\nolimits_{i \in \{0\} \cup S' \cup D'} x_{i,N+1}^k = 1, \quad \forall k \in K \tag{5}$$

$$\sum\nolimits_{j \in G' \cup \{N+1\}} x_{sj}^k \leq 1, \quad \forall k \in K, s \in S' \tag{6}$$

$$\sum\nolimits_{i \in V_0} x_{ij}^k \leq 1, \quad \forall k \in K, j \in G' \tag{7}$$

$$\sum\nolimits_{i \in V_0} x_{ij}^k - \sum\nolimits_{i \in V_{N+1}} x_{ji}^k = 0, \quad \forall k \in K, j \in V \tag{8}$$

$$\sum\nolimits_{r \in R} y_{ri}^k \leq M_1 \sum\nolimits_{j \in V_{\mathrm{N}+1}} x_{ij}^k, \quad \forall k \in K, i \in G' \tag{9}$$

$$y_{ri}^k = 1 \Rightarrow \sum\nolimits_{j \in V_0} x_{ji}^k = \sum\nolimits_{j \in G' \cup D'} x_{jd_r}^k, \quad \forall k \in K, i \in G', r \in R \tag{10}$$

$$x_{ij}^k = 1 \Rightarrow q_j^k = q_i^k + \sum\nolimits_{r \in R} y_{rj}^k, \quad \forall k \in K, i \in V_0, j \in G' \tag{11}$$

$$x_{ij}^k = 1 \Rightarrow q_j^k = q_i^k - \sum_{r \in R} \sum_{g \in G'} y_{rg}^k, \quad \forall k \in K, i \in G\prime, j \in D' \tag{12}$$

$$0 \leq q_i^k \leq Q^k, \quad \forall k \in K, i \in V_{0,N+1} \tag{13}$$

$$B_j^k \geq B_i^k + u_i + t_{ij} - M_2(1 - x_{ij}^k), \quad \forall k \in K, i \in V_0, j \in V_{N+1} \tag{14}$$

$$B_j^k \geq B_s^k + \tau_s^k + t_{sj} - M_2(1 - x_{sj}^k), \quad \forall k \in K, s \in S', j \in \{G' \cup N + 1\} \tag{15}$$

$$x_{ij}^k = 1 \Rightarrow A_j^k = B_i^k + t_{ij} + u_i, \quad \forall k \in K, i \in G\prime \cup D', j \in D' \tag{16}$$

$$W_i^k \geq B_i^k - A_i^k - M_2(1 - p_i^k), \quad \forall k \in K, i \in D' \tag{17}$$

$$p_i^k = \sum_{j \in V} x_{ji}^k, \quad \forall k \in K, i \in D' \tag{18}$$

$$A_{d_r}^k - B_i^k - u_i \leq L_i + M_2\left(1 - y_{ri}^k\right), \quad \forall k \in K, (r, i) \in A_C \tag{19}$$

$$e_i \leq B_i^k \leq l_i, \quad \forall k \in K, i \in D' \tag{20}$$

Vehicle energy constraints:

$$E_0^k = E_{init}^k, \quad \forall k \in K \tag{21}$$

$$E_{min}^k \leq E_i^k \leq E_{max}^k, \quad \forall k \in K, i \in V \tag{22}$$

$$x_{ij}^k = 1 \Rightarrow E_j^k = E_i^k - \beta^k c_{ij}, \forall k \in K, i \in V_0 \backslash S', \quad j \in V_{N+1} \tag{23}$$

$$x_{ij}^k = 1 \Rightarrow E_j^k = E_s^k + \alpha_s \tau_s^k - \beta^k c_{sj}, \quad \forall k \in K, s \in S', j \in \{G' \cup N + 1\} \tag{24}$$

Charging scheduling constraints:

$$v_s = \sum_{k \in K} \sum_{j \in G' \cup N+1} x_{sj}^k, s \in S' \tag{25}$$

$$v_h \le v_l, \forall h, l \in S'_o, o \in S, h < l \tag{26}$$

$$\sum_{k \in K} B_h^k \ge \sum_{k \in K} B_l^k + \sum_{k \in K} \tau_l^k - M_2(2 - v_h - v_l), \quad \forall h, l \in S'_o, o \in S, h < l \tag{27}$$

$$\tau_s^k + B_s^k \le M_2 \sum_{j \in G' \cup N+1} x_{sj}^k, \quad \forall s \in S', k \in K \tag{28}$$

$$v_s \le 1, \quad s \in S' \tag{29}$$

Domain of variables:

$$x_{ij}^k \in \{0,1\}, \quad \forall k \in K, i, j \in V_{0,N+1} \tag{30}$$

$$y_{ri}^k \in \{0,1\}, \quad \forall k \in K, r \in R, i \in G' \tag{31}$$

$$\tau_s^k \ge 0, v_s \ge 0, \quad \forall k \in K, s \in S' \tag{32}$$

$$A_i^k \ge 0, B_i^k \ge 0 \quad \forall k \in K, i \in V_{0,N+1} \tag{33}$$

$$p_i^k \in \{0,1\}, W_i^k \ge 0, \forall k \in K, i \in D' \tag{34}$$

The operator $\Rightarrow$ means that if the left-hand side of the equations is true, then their right-hand side constraints need to be satisfied. Equation (2) states that each customer can be assigned to at most one meeting point. Equation (3) imposes a customer's maximum walking distance to meeting points. Equations (4)–(5) and (8) are the flow conservation. Equations (6)–(7) state that each meeting point and each charger can be visited by a vehicle at most once. Equation (9) ensures that a meeting point assigned to a customer must be visited by a vehicle. Equation (10) ensures that if customer r is assigned to the meeting point i, the drop-off location of customer r (i.e. d_r) must be served by the same vehicle k. Equations (11)–(13) manage the passenger loads at meeting points and transit stations under vehicle capacity. Equations (14)–(15) ensure the consistency of the beginning of service time at bus nodes and charger nodes with a charging duration of τ_s^k, respectively. Equation (16) defines the relationship between vehicle arrival time and the beginning time of service. Equations (17)–(18) determine the vehicle waiting time at transit stations when arriving earlier than its buffer time. Equation (19) limits the customer's maximum riding time (i.e. 1.5 times the direct riding time). Equation (20) sets up the arriving time constraints (within a fixed buffer time before the departure time of trains) of vehicles at transit nodes. Equations (21)–(22) initiate the state of charge of vehicles and their upper and lower bounds. Equations (23)–(24) are energy conservation constraints. Equations (25)–(29) are charging scheduling constraints with capacitated charging stations. Equations (30)–(34) specify the domain of variables.

Since the problem is NP-hard, exact solutions are possible only for small instances. Thus, we previously developed a hybrid deterministic annealing (DA) metaheuristic for larger instances (Ma et al. 2023a b). The proposed hybrid metaheuristic consists of three steps: 1. Assign customers to nearby meeting points; 2. Optimize electric vehicle routing and charging scheduling with partial recharge policy and charging synchronization; 3. re-optimize the solution obtained in Step 2 to insert unserved customers and re-optimize current routes based on a metaheuristic approach. The algorithm was tested on 20 test instances with up to 100 customers and 49 used meeting points under different initial battery levels and demand distributions (peaked and non-peaked demand scenarios). The proposed algorithm efficiently found good-quality solutions in a short computational time. Compared to a 4-h solution from the MILP solver, the average and best solution gaps are 4.02% and 3.31% respectively. The reader is referred to the aforementioned studies for a more detailed description. In the following section, we apply the developed metaheuristic to a real-world case study. The focus is on the effect of different system parameters and their configuration to obtain a better performance of the system.

3.2 Case Study Design

A case study mimics a real-world scenario for Belgian cross-border workers commuting from Arlon to Luxembourg during the morning peak hour. We assume that the MP-EFCS service is provided in the Arlon region to connect customers to the main train station with one railroad line (line 50) to Luxembourg. During morning peak hours (6:00–9:00), trains depart every 15 min on average. Five test instances are generated in this context with customer requests randomly distributed within a radius between 1.5 km and 6km. The total number of requests is assumed as 600 from 6:00–9:00 which corresponds to ~ 50%[1] of total train trips for the Arlon to Luxembourg cross-border workers based on the 2017 Luxmobil survey (Lambotte et al., 2021). Customers' desired arrival times at the station corresponding to the train departure time follow a normal distribution and are randomly generated for each test instance. With a maximum walking distance of customers of 1.0 km, no customers are assumed to walk directly to the station. Using a grid system, meeting points are set 1.2 km apart for the base scenario. To facilitate the analysis, a homogenous 24-seat shuttle is used. However, the proposed method can be adapted by considering a heterogeneous fleet with multiple depots without difficulty. We assume that the train station and the depot are located at (0, 0) and the two DC fast chargers are located at (0, 0) and one at (1, 0) (in km), respectively (see Fig. 1). Note that the impact of different charging infrastructure configurations will be analyzed in our future work. To invoke charging operations, initial states of charge of vehicles are set randomly between 50% and 100% of battery capacity (Table 1).

[1] Based on the number of Arlon's cross border workers (16900 i.e. 9% of Luxembourg's cross border workers in 2023) multiplied by the mode share of train for this population (7.9%). As a result, a total of 1335 train trips on weekdays are estimated for the cross border workers from Arlon to Luxembourg.

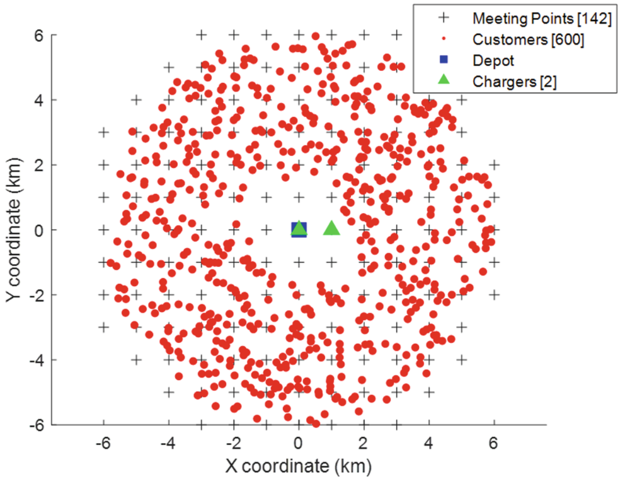

Fig. 1. Example of a test instance with 600 requests during the morning peak hour in the study area (meeting point separation distance is 1.0 km).

Table 1. Summary of the parameter setting of the case study.

Parameter	Value	Parameter	Value
Passenger Capacity	24	Maximum walking distance (km)	1.0
Battery Capacity (kWh)	118	Nearest separation distance between meeting points (km)	1.2
Energy consumption rate (kWh/km)	1.23	Walking speed (km/hour)	5.1
Bus speed (km/hour)	30	Detour factor	1.5
Number of chargers	3	Charging power (kWh/hour)	50

3.3 Computational Experiment Settings

We design four computational experiments to investigate the effects of different parameters on the performance of the system. A set of key performance indicators (KPIs) are used to evaluate the system performance, including the number of used vehicles, service rate, average walking distance, average in-vehicle travel time (IVT), additional vehicle waiting time at transit stations (earlier arrivals before the buffer time), total kilometers traveled by vehicles (KMT), the average number of served customers per KMT, average customers per meeting point, and total charging time of the fleet.

These experiments first evaluate the effect of meeting point availability, and user-defined weights (in the objective function) on KPIs, while keeping other system parameters unchanged based on the base case (described below). In doing so, we can isolate the effect when changing the value of one single system parameter. Then we configure these parameters over a set of values to improve the performance of the system compared to the base case. All experimental results are based on the average performance of the five test instances. For each test instance, a 3-run best solution is used. Following our previous study (Ma et al., 2023b), the same tuned algorithmic parameters of the metaheuristic are used for this study.

The set of tested values is set as follows:

- Fleet size: $|K| \in \{10,12,14,16\}$
- Meeting point separation distance (in meters): $\tilde{d} \in \{1000, 1200, 1400\}$
- Weights in the objective function: $\lambda_1 \in \{0, 1, 2, 3\}$, $\lambda_2 \in \{0, 1,2, 3\}$, $\lambda_3 \in \{0,1, 2,3\}$

The penalty for rejecting customers (λ_4) is set as 40 for all experiments. This is based on our preliminary studies showing that using a higher penalty results in similar performance. The parameters of the **base case** are set as $\lambda_1 = \lambda_2 = \lambda_3 = 1$, the meeting point separation distance = **1.2 km**, and the fleet size = **14 vehicles**. Note that the effect of other system parameters can be analyzed similarly as well (e.g. buffer time at transit stations, detour factor for specifying riding time constraints, etc.).

The computational experiments are conducted on a PC with Intel(R) Core(TM) i7-11800H, 16 logical processors, and 64 GB of memory. The implementation of the metaheuristic algorithm is based on Julia and uses Gurobi MIP solver version 10.0.2.

4 Results

4.1 The Impact of Meeting Point Availability

We change the MP separation distance from 1000 m to 1400 m, giving the base-case parameter setting. Note that in our experiments, the meeting points (MPs) are organized as a grid system (see the example in Fig. 1). An X km MP separation distance results in the furthest away from the grid center of $X/\sqrt{2}$ km. So the maximum walking distance of 1 km will not be an issue for the 1400 m case ($1.4/\sqrt{2} = 0.9899$ km). However, the MP separation distance will change the number of MPs within walking distance and hence the flexibility of pickup locations. As a result, more customers are served when there are more MPs (e.g., 99.6% are served with MP dist = 1000 m) than the case with fewer MPs (e.g., 96.3% are served when MP dist = 1200 m).

The smaller MP separation distances (i.e., more MPs) result in shorter KMTs (-1.62% and −5.44% compared to using 1200 m and 1400 m, respectively). It is because as more MPs become available, the chances for multiple customers to share the same MP increas−s, and the average number of customers per MP (cus/MP) increases (see Table 2). Hence, the number of used MPs decreases leading to less KMT as well as less total charging time (see Table 2). These results indicate that more available MPs allow the system to reduce operational costs by jointly optimizing customer-to-meeting-point assignment and vehicle routing.

4.2 The Effects of the Objective Function Parameters

We examine various user-defined weights in the objective function: λ_1 is related to total vehicle routing and charging times, while λ_2 and λ_3 addresse walking distance and excess waiting time at a transit station. Parameter set 1 (see Table 3) only considers the total

Table 2. Key metrics of the MP-EFCS with different separation distances between meeting points.

MP dist	# of MP	Service rate (%)	Walking dist	IVT	Charging time	KMT	cus/KMT	cus/MP	CPU (sec)
1000	141	99.6	0.59	9.95	9.41	822.89	0.73	3.14	1093
1200	100	96.3	0.58	9.92	30.62	856.10	0.68	2.81	1331
1400	74	91.7	0.57	10.03	41.13	870.24	0.63	2.56	949

routing time and charging time; set 2 minimizes total walking time and excess waiting time at transit stations; set 3 is the base case with equal weights. Parameter sets 4 and 5 increase the weights of λ_1 in favor of operators. Table 3 shows the effect of λ_1 on the system performance. First, solely minimizing customers' walking distance and excess waiting time of vehicles at transit stations results in the highest KMT with significant unserved customers (serve rate is only 71.6%, the line of parameter set 1 on Table 3). Conversely, only minimizing the total vehicle routing time and charging time results in the highest average walking distance (0.61 km). Compared to the base case, parameter set 5 gives the lowest KMT (813.9 km) and significantly lower total charging time (2.8 min), suggesting both the operator's and customer's costs need to be considered to have synergies.

Table 3. Effects of λ_1.

Para set	λ_1	λ_2	λ_3	Service rate(%)	Walking dist	IVT	Charging time	KMT	cus/KMT	cus/MP	CPU (s)
1	0	1	1	71.6	0.46	9.87	54.1	877.0	0.49	1.68	1397
2	1	0	0	97.3	0.61	9.91	26.7	849.6	0.69	2.80	999
3	1	1	1	96.5	0.58	9.90	38.1	859.8	0.67	2.81	988
4	2	1	1	97.9	0.58	9.97	10.6	834.0	0.70	2.89	872
5	**3**	**1**	**1**	**97.2**	**0.58**	**9.97**	**2.8**	**813.9**	**0.72**	**2.85**	**1013**

Remark: Fleet size is 14 and λ_4 = 40. Excess waiting time at the transit station is 0 for all tested cases.

For the effects of λ_2(Table 4), the result is as expected that increasing λ_2 results in shorter average walking distance of customers. Regarding λ_3, there are no significant effects on the system performance compared with the base case.

4.3 Optimizing System Parameter Configuration

Based on the above analysis, we search optimal parameter configuration concerning fleet size, meeting point separation distance, and λ_1 and analyze the trade-off of operational costs and customers' inconvenience. We considered:

Table 4. The effect of λ_2 and λ_3.

λ_1	λ_2	λ_3	Service rate (%)	Walking dist	IVT	Charging time	KMT	cus/KMT	cus/MP	CPU (s)
1	**0**	1	97.6	0.61	9.78	47.0	866.3	0.68	2.83	843
1	**1**	1	96.5	0.58	9.90	38.1	859.8	0.67	2.81	988
1	**2**	1	97.1	0.58	9.98	26.1	847.9	0.69	2.85	859
1	**3**	1	95.3	0.57	9.87	30.2	853.9	0.67	2.81	992
1	1	**0**	96.5	0.58	9.97	36.1	860.3	0.67	2.77	1102
1	1	**1**	96.5	0.58	9.90	38.1	859.8	0.67	2.81	988
1	1	**2**	95.2	0.58	9.86	40.5	863.0	0.66	2.79	996
1	1	**3**	98.2	0.58	9.98	35.0	856.2	0.69	2.84	916

Remark: PS: Parameter set; Fleet size is 14 and λ_4 = 40. Excess waiting time at the transit station is 0 for all tested cases.

- Fleet size: $|K| \in \{12,13,14\}$
- Meeting point separation distance: $\tilde{d} \in \{900, 1000, 1100\}$
- $_1$: $\lambda_1 : \lambda_1 \in \{1, 2, 3\}$ (with $\lambda_2 = \lambda_3 = 1$)

Keeping other parameters as default, this gives 27 combinations. Table 5 summarises the best system parameter configuration only. Compared to the base case, using a smaller MP distance and higher λ_1 results in significant total KMT savings (−10.8% compared with the base case for 14 vehicles) with little increase in average walking time (0.62 or 0.63 km compared with 0.58 km for the base case). When reducing fleet size from 14 to 13 and 12, the configured system parameters allow for reducing further operational costs (−11.4% and 16.3% in terms of KMT) with +0.3% and −3.1% unserved customers. The result suggests that the best performance is achieved using a smaller MP distance with the joint configurati−on of system parameters to minimize the overall system costs.

4.4 Benefits of the MP-EFCS Service Compared to Door-to-Door DARP

We further compare the performance of the MP-EFCS service with the door-to-door DARP. The objective function of the DARP minimize total travel time and charging time. Table 6 shows that while DARP using diesel vehicles (lower bound) requires 47 vehicles on average, MP-EFCS needs only 14 vehicles, a 70.2% reduction. Besides, the MP-EFCS service reduces 49.4% of KMT with an average of 0.79 customers per KMT, almost doubling the efficiency. Note that while the fleet use cost is not incorporated in the objective function, our metaheuristic attempts to reduce the number of used vehicles in the large neighborhood search process.

By converting the KMT saved by EVs into CO_2 savings following Rosero et al. (2020), we estimate a yearly reduction of nearly 298 tons of CO_2 emissions assuming that a fleet traveling 1000 km per day for 365 days (i.e., 365*1000*0.816 kg = 297.84).

Table 5. Best system parameter configurations for different fleet sizes.

Best configuration	MP dis	# used vehicle	λ_1	Service rate	Walking dist	IVT	Charging time	KMT	cus/KMT	cus/MP
V14	900	14	3	100.0	0.63	9.92	0.0	763.6 (−10.8%)	0.79	3.36
V13	900	13	3	99.4	0.62	9.88	5.4	758.5 (−11.4%)	0.79	3.35
V12	900	12	3	96.0	0.63	9.89	27.5	716.6 (−16.3%)	0.80	3.32
Base case	1200	14	1	96.3	0.58	9.92	30.6	856.1	0.68	2.81

Remark: Excess waiting time at the transit station is zero for all test cases. Based on the average performance of the 5 test instances with the 3-run best solution.

Table 6. Comparison of the KPIs between the MP-EFCS and door-to-door DARP

Type of service	Service rate (%)	# of used vehicles	IVT	KMT	cus/KMT	cus/MP
DARP[1]	100.0	47	10.6	1508.9	0.40	-
MP-EFCS	100.0	14 (−70.2%)	9.92 (−6.4%)	763.6 (−49.4%)	0.79 (+97.5%)	3.36

Remark: 1. Using diesel vehicles to have lower bounds.

5 Discussion and Conclusions

DRT often aims to improve fixed-route public transport in rural areas. However, DRT's high operational costs often lead to service terminations (Haglund et al. 2019). The push towards zero-emission transit and EV deployment further complicates DRT by demanding the joint optimization of routes and charging. Addressing these, our previous studies proposed a meeting-point-based EV-DRT model for a cleaner and more efficient service (Ma et al. 2023 a, b). In this study, we investigate the effects of different system parameters on a set of key performance indicators using a set of real-world size test instances. Simulation experiments revealed several findings and limitations of the proposed methodology.

a. The influence of meeting point availability is particularly important to reduce the number of unserved customers and routing costs (in terms of KMT). When the availability of meeting points is higher, the system allows to better configure customer assignment and routing jointly to enhance the system efficiency. While we conducted exploratory experiments, the operators could consider all possible meeting points (street corners, parking places, existing bus stops, etc.) in the service area to have the best performance of the system. When extending the problem to dynamic cases (i.e. allowing new requests to be inserted in the current routes after starting the service), dynamic meeting point assignment methodology can be applied (Czioska et al. 2019).

b. Evaluating fleet size, meeting point availability, and objective function weights simultaneously showed that an optimal configuration significantly reduces vehicles used and total KMT without compromising customer convenience. This suggests that this effort is necessary to optimize the system's performance and reduce operational costs.
c. When comparing the MP-EFCS services with traditional DARP, there is a clear advantage for this kind of meeting-point-based service. Our case study shows that it can reduce 70.2% of the number of used vehicles and 49.4% of KMT when the ride time constraint of customers is characterized by a detour factor of 1.5. This suggests a good potential for applying the MP-EFCS service to reduce the operational costs of traditional DRT services.
d. In terms of methodology, we show that the developed hybrid metaheuristic can solve real-world problems within reasonable computational time. To achieve better performance, we are currently improving the algorithm by allowing different customer-to-meeting-point assignment outcomes to be explored jointly and incorporating new local destroy-repair local search operators in the large neighborhood search process.

Future extensions include studying urban morphology's effect on the performance of the meeting-point-based feeder services; joint charging infrastructure and fleet size planning by considering both first- and last-mile feeder service with heterogeneous and mixed fleets (gasoline and EVs).

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Competing interests: None.

Declarations. Availability of Data and Material: https://github.com/tym2021/datasets-for-electrified-meeting-point-based-feeder-bus-services.git.

Appendix A. Notation

Sets	
G	Set of physical meeting points, i.e. $G = \{1, ..., N_G\}$
G'	Set of dummy (duplicate) meeting point vertices (no des)

(*continued*)

(*continued*)

D	Set of physical transit stations, i.e. $D = \{1, ..., N_D\}$
D'	Set of dummy (duplicate) transit station vertices
S	Set of physical chargers, i.e. $S = \{1, ..., N_S\}$
S'	Set of dummy (duplicate) charger vertices
R	Set of customers (i.e. location of origin of customers)
K	Set of electric buses
$\overline{V}$	Set of all vertices, i.e. $\overline{V} = G' \cup D' \cup S' \cup R \cup \{0, N+1\}$
V	Subset of vertices, i.e. $V = G' \cup D' \cup S'$
$V_0, V_{N+1}, V_{0,N+1}$	$V_0 = V \cup \{0\}$, $V_{N+1} = V \cup \{N+1\}$, $V_{0,N+1} = V \cup \{0, N+1\}$
$\mathcal{A}_c$	Set of walking arcs from customers' origins to meeting points, i.e. $\mathcal{A}_C = \left\{(r, j) \vert r \in R, j \in G'\right\}$
$\mathcal{A}_B$	Set of bus arcs
Parameters and auxiliary variables	
$0, N+1$	Two duplicate instances of the depot
T	Planning horizon
A_i^k	Arrival time of bus k at vertex i
B_i^k	Beginning time of service of bus k at vertex i
p_i^k	Indicator: 1 if node i is visited by bus k, 0 otherwise
W_i^k	Waiting time of bus k at node i
q_i^k	Passenger load of bus k when leaving vertex i
E_i^k	The battery energy level of bus k when arriving at the vertex i
Q^k	Capacity of bus k
$E_{min}^k, E_{max}^k, E_{init}^k$	The minimum, maximum, initial state of charge (SOC) of bus k
w_{ri}	Walking distance from customer r origin to meeting point $i \in G'$
c_{ij}	Distance from vertex i to vertex j
t_{ij}	Bus travel time from vertex i to vertex $j \forall i, j \in V_{0,N+1}$. Note that t_{rj} is the walking time from customer r origin to meeting point j, $\forall r \in R, j \in G'$
L_i	Maximum ride time for customers picked up at node i. Calculated as 'straight line' ride time multiplied by a detour factor
w_{max}	Maximum walking distance
u_i	Service time at vertex $i \in V$
e_i, l_i	Earliest and latest starting times of service at vertex $i \in V_{0,N+1}$
d_r	Drop-off transit station dummy node of customer r
α_s	The charging rate of charger $s \in S'$
β^k	Energy consumption rate per kilometer traveled for bus k

(*continued*)

(*continued*)

M	Large positive number
λ	Weighting coefficient for the objective function
Decision variables	
y_{ri}^{k}	Indicator: 1 if customer r is assigned to bus k and meeting point i, 0 otherwise
x_{ij}^{k}	Indicator: 1 if arc (i, j) is traversed by bus k, 0 otherwise
τ_{s}^{k}	Charging duration for bus k at charger s, $s \in S'$

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Advances on the Next Generation Short-Medium Range Aircraft Rear End: The CleanSky 2 Project IMPACT

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Abstract. This paper aims at presenting the results of the CleanSky 2 European project IMPACT (GA no. 885052), granted under the Large Passenger Aircraft Integrated Technology Demonstrator (LPA-ITD), aiming at optimizing the rear-end design for the next generation Short and Medium Range (SMR) A320-like aircraft. Specifically, the project has investigated a Forward Swept Horizontal Tail Plane (FSHTP) enhanced with a Leading-Edge eXtension (LeX) device. The activities have focused on the optimisation of the horizontal stabilizer, accounting for the coupled aerodynamic, aeroelastic and, for the first time, icing behaviour. The optimal solution provides significantly better lift performance of the tailplane (i.e. up to 12.4% increase in C_L), limiting the drag penalty to below 1.0% in cruise condition (i.e. between 0 and 2 degrees of Angle of Attack).

Keywords: IMPACT CleanSky-2 · rear-end · 3D icing · forward swept horizontal stabilizer · leading-edge extension · horizontal tailplane optimisation

1 Introduction

The urgency of a deep decarbonization of our economies and lifestyles and the transition to a circular economy has never been greater. Transport accounts for approximately one-fourth of greenhouse gas emissions from the European Union, with civil air transport responsible of 14% of these, growing at a steady rate of 5–7% per year. Air transport is inherently carbon-intensive, and due to its significant power and energy requirements, moving away from energy-dense fossil fuels is extremely challenging. Within the European Union's decarbonization plan, four synergistic pillars have been identified to achieve carbon neutral air transport: (i) the improvement of aircraft technologies, (ii) the adoption of sustainable aviation fuels (iii) the implementation of economic measures, and (iv) the deployment of better air traffic management. Solely focusing on the technology improvement dimension, it is expected to deliver up to 38% emission reduction by

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2050 against the 2020 baseline, by introducing hybrid-electric and hydrogen propulsion, better and lighter aircraft design and fully electric aircraft auxiliaries. In this framework, the CleanSky2 IMPACT project (GA no. 885052) has investigated a novel design for the rear-end of the next generation Short and Medium Range (SMR) A320-like aircraft, focusing on a Forward Swept Horizontal Tail Plane (FSHTP) enhanced with a Leading-Edge eXtension (LEX) device to deliver better aerodynamic and aeroelastic performance. Moreover, the delivered design also aims at ensuring sufficient ice-tolerance and maneuverability in ice conditions. The work has been conducted in close collaboration with AIRBUS, informing the design of the next generation SMR aircraft.

2 Aerodynamics of the Forward Swept Horizontal Stabilizer and Introduction of the Leading-Edge eXtension (LEX)

Transonic aircraft wings are typically back-swept (positive) due to gust load considerations. Negative (forward) sweep angles would subject the wings to higher gust loads, making them heavier. However, several studies have investigated the using of forward-swept wings to exploit their aerodynamic advantages. Aeroelastic tailoring techniques can mitigate coupling between flexional and torsional deformation, making this design advantageous [1, 2]. Compared to aft-swept wings, forward-swept lifting surfaces offer several benefits. They exhibit a higher shock-sweep angle for a given leading edge sweep angle, allowing for smaller leading edge sweep angles while maintaining equivalent sweep angles at the quarter chord line [3]. Additionally, airflow over forward-swept wings move from the root to the tip, resulting in higher stall angles [4]. This can lead to increased maximum aerodynamic forces or enable a reduction in tailplane area to achieve the same force, potentially reducing drag and weight. To further enhance the maximum lift capabilities of a forward-swept tailplane, a passive LEX device can be introduced (Fig. 2-right). This serves for enhancing wing aerodynamics during high angles of attack and low-speed flight. By altering the wing's leading edge, the LEX boosts lift generation by altering airflow patterns, delaying flow separation, and enabling sustained lift at higher angles of attack, such as take-off and landing phases. Secondly, the LEX improves aircraft stability and control by managing wing airflow, reducing stall tendencies, preventing tip stalls, enhancing pitch stability, and possibly delaying separation, reducing drag. The IMPACT project has carried out extensive aerodynamic investigations on the rigid aerodynamics of forward swept tail for the SMR aircraft baseline (A320-like) by using high-fidelity CFD-RANS simulations.

Investigations into isolated tailplanes have confirmed that a forward-swept tailplane has better maximum lift capabilities compared to a back-swept tail. However, when the forward-swept tailplane is coupled with the fuselage body, the resulting angle at the intersection area promotes flow separation leading to the loss of the aerodynamics advantages over the conventional tail. This can be appreciated by comparing the tail lift coefficients of Fig. 1-(a). The results achieved exhibits that the introduction of the LEX helps to maintain a smoother airflow and achieve the same maximum lift coefficient as the reference conventional tailplane, despite having a tail surface that is 6% smaller than the conventional empennage. Anyway, by introducing the LEX and by reducing the sweep angle at the leading edge drag at high speed (i.e., cruise conditions) and angle

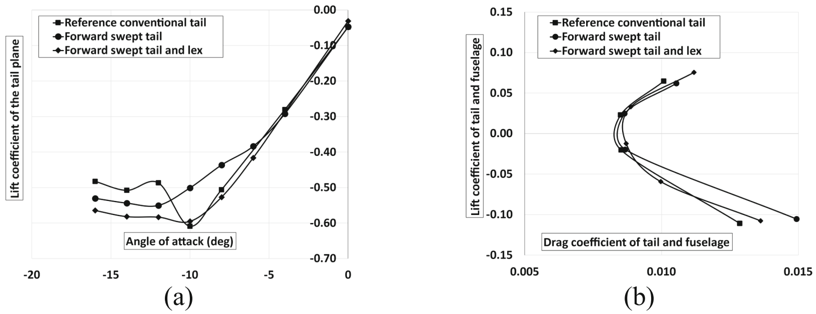

Fig. 1. Comparison between the reference conventional tail and forward swept and lex that minimize the total wetted area: (a) lift curve variation with respect to the angle of attack at M = 0.2 and sea level altitude (b) drag polar curves at M = 0.78 and 39,000 ft flight altitude.

of attack of about 4 degrees resulted to be higher because of increased compressibility effects and higher lift curve slope. Figure 2 shows the contour of the wall shear stress for both the LEX off and on configurations, highlighting how the vortex system generated by the LEX helps to maintain better flow attachment at the tail root sections. The results on the rigid aerodynamic has been then enhanced with the aeroelastic and icing behaviour, to drive the final coupled optimization (Sect. 4).

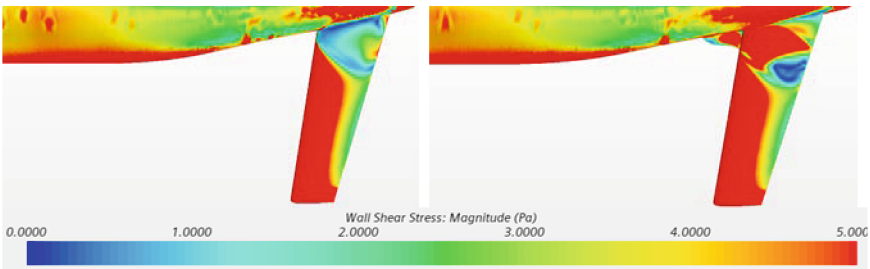

Fig. 2. Contour of wall shear stress (Pa) at M = 0.2, sea level, AoA = -10 deg. Deep blue regions represents separated flow. FSHTP without (left) and with LEX, (right). Picture generated with ANSYS®.

3 3D Ice Accretion on the FSHTP, and Degradation of the Maneuverability Performance

A key design feature for the horizontal stabilizer is its ability to deliver sufficient downward lift for round out and flare, following 45 min holding in severe icing conditions. As the empennage is intended to have no active ice protection system, it is sized to ensure sufficient maximum lift coefficient with the worst such case ice accretion, potentially bringing weight and drag penalties. Under the IMPACT project, the maximum lift coefficient deficit under icing conditions was mapped in the design space to inform the multi-objective optimization. This was achieved using CFD-based inflight icing simulation to calculate the worst-case ice accretion and CFD to calculate the clean (uniced) and iced maximum lift coefficients (C_L) at selected design points. ANSYS FENSAP-ICE was used to carry out multishot icing simulations on the FSHTP with LEX, with low (10°), intermediate (15°) and high (20°) forward sweep and, separately, with low sweep and the LEX with 10% and 20% increased spanwise and chordwise extents. The 20-shot, full aircraft-based icing calculations simulated 45-min holding pattern in icing conditions at 16,000' and -12 °C with a VCAS of 220 kts. The cloud conditions were LWC 0.38 g/m^3 and a seven bin Langmuir-D droplet size distribution with a mean volumetric diameter of 20 µm, in accordance with FAR 25 Appendix-C. Subsequently, ANSYS-Fluent was used with the clean and iced full-fuselage-with-empennage geometries to calculate the respective C_L versus angle of attack and, thus, the maximum C_L values and iced C_L deficits, which were integrated into the horizontal stabilizer optimization. The results showed increased forward sweep reducing the iced maximum C_L deficit, as seen clearly in Fig. 3. Closer inspection revealed that higher sweep increases the lift deficit at the inner spans near the LEX but, more so, reduces the deficit at the outer spans. The high sweep suction surface Wall Shear Stress (WSS) contours with streamlines for the high sweep geometry in Fig. 3 show patches of high WSS where the sweep promotes mid and outer span flow reattachment. More comprehensive details can be found in [5].

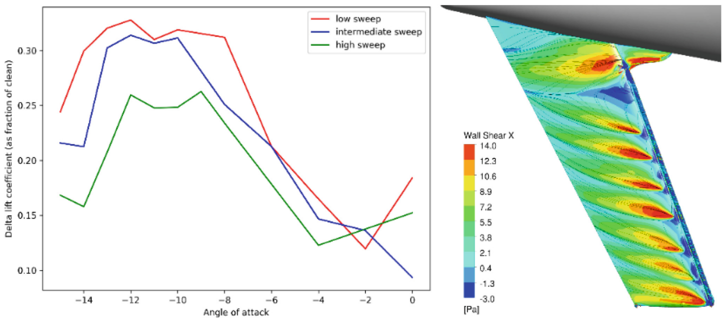

Fig. 3. Iced horizontal stabilizer lift deficit versus angle of attack for low, intermediate, and high forward sweep (left) and suction surface axial wall shear stress with surface streamlines. Right hand side picture generated with ANSYS®.

4 Aerodynamics and Aerostructural Optimisation of the Rear-End, Including the Effect of Icing

To efficiently explore various optimization problems by manipulating design variables, constraints, and objective functions related to the aerodynamic, aeroelastic and icing performance of the FSHTP (presented in the sections above), IMPACT has developed a rapid optimization approach based on a design of experiments which feeds a response surface for the aerodynamic performance prediction of the Advanced Rear End (ARE) concept. This response surface is integrated into a functional workflow for conducting optimization tasks within the RCE environment [6]. The output of the optimization runs has been validated through dedicated CFD-RANS simulations. The optimum obtained with this process regards the so-called rigid optimization, and it has been later enhanced by accounting for icing and aeroelastic effects. More details on the latter are reported in [7]. The optimization problem is mathematically defined as reported in (1), enhancing the reliability of pure aerodynamic (rigid) optimization results by incorporating additional information about aeroelastic effects and the impact of icing on the decay of C_{Lmax}. This problem aims to minimize drag across the entire range of cruising angles of attack (AoA), maximize the maximum lift coefficient (C_{Lmax}) of the tail, and simultaneously minimize the loss of CL_{max} caused by ice. This optimization was performed under two sets of constraints: the tail stability characteristics, specifically the pitching moment coefficient slope, and a geometrical limitation on the longitudinal position of the tailplane to prevent excessive fuselage stretching.

$$\begin{cases} \text{minimize} \\ \left[\mathbf{W}_1 \times \left(\sum_{AoA=-4deg}^{AoA=4deg} \mathbf{C_D}_{AOA} \right) + W_2 \times \left(\frac{1}{\left| \mathbf{C_L}_{max,negative\ FLex\ NO\ ICE} \right|} \right) + W_3 \times \boldsymbol{\Delta C_L}_{max\ ICE} \right] \\ \text{Where:} \\ \mathbf{W}_1 = W_2 = W_3 = 0.33 \\ \text{With:} \\ \left(\left| \mathbf{C_M}_{\alpha TAIL\ Flex} \right| - \left| \mathbf{C_M}_{\alpha TAIL\ Flex,\ target} \right| \right)_{cruise\text{-}and\text{-}stall} \geq 0 \\ \mathbf{X}_{apex,reference_{FSHTP}} - X_{apex_{FSHTP}} \geq 0 \end{cases} \tag{1}$$

The results of the optimisation problem are reported in Table 1 against the reference HTP (baseline) and the reference FSHTP, with the performance results reported in Table 2. Results clearly highlight that icing penalties to CL_{max} play a major role in driving the optimization. It has been found that the rigid CL_{max} in ice-off conditions could still be up to 12.4% higher than the conventional tail arrangement. However, the LEX design is more stressed, which has a detrimental impact on the induced angle of

Table 1. Comparison of the geometric characteristics of the optimum configuration with respect to reference HTP and FSHTP

	Opt.	Reference HTP	Ref. FSHTP
AR_H	5.928	5.76	5.80
C_{LEX}/C_{root}	1.933	---	---
b_{LEX}/b_H	0.139	---	---
S_H	30.966(m^2)	31.36 (m^2)	30.99 (m^2)
Sweep	−19.550(deg)	32.0 (deg)	−15 (deg)
Taper	0.405	0.336	0.700
Xapex	34.513(m)	31.585 (m)	33.765 (m)

attack on the tail sections located after the LEX. This, in turn, negatively affects the compressibility drag. In fact, at AoA around ± 4 degrees, a significant increase in drag has been observed, although the drag penalty is within 1% in cruise conditions (0–2 deg. AoA).

Table 2. Aerodynamics of the optimum configuration vs. reference HTP.

Parameter	Opt.	Ref. HTP	Δ(%)
C_{Lmax} negative	−0.1664	−0.1520	**+9.45%**
C_{Lmax} negative flexible	−0.1674	−0.1490	**+12.40%**
$C_{D\_tot\ (AoA = 0deg)}$	0.0085	0.0086	**−0.95%**
$C_{D\_tot\ (AoA = 2deg)}$	0.0086	0.0085	**+0.97%**
$C_{D\_tot\ (AoA = 4deg)}$	0.0110	0.0100	**+9.63%**
$C_{D\_tot\ (AoA = -4deg)}$	0.0146	0.0129	**+13.42%**
C_{Ma} Tail cruise	−0.0736	-0.0707	**+4.10%**
C_{Ma} Tail cruise flexbile	−0.0752	−0.0672	**+11.92%**
C_{Ma} Tail low speed	−0.0607	−0.0572	**+6.18%**
C_{Ma} Tail low speed flexible	−0.0611	−0.0561	**+9.04%**
C_{La} Tail cruise	0.0187	0.0171	**+9.16%**
C_{La} Tail cruise flexible	0.0191	0.0162	**+17.37%**
C_{La} Tail low speed	0.0155	0.0145	**+6.69%**
C_{La} Tail low speed flexible	0.0156	0.0142	**+9.56%**
Eta Flex low speed	1.0064	0.9800	**+2.69%**
Eta Flex high speed	1.0214	0.9500	**+7.52%**
Delta CL max ICE	-0.1226	–	–

5 Conclusions

This paper presents the results of the coupled aerodynamic, aeroelastic and icing-tolerant optimisation of the horizontal stabilizer for the next generation Short and Medium Range (SMR) A320-like aircraft. This is based on a Forward Swept Horizontal Tail Plane (FSHTP) planform enhanced with a Leading-Edge eXtension (LeX) device. The results show that the optimal solution provides significantly better lift performance of the tailplane limiting the drag penalty in cruise condition.

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Market-Based Measures for International Aviation and Shipping: Lessons Learned from a Cross-Sectoral Analysis of EU ETS

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Abstract. The reduction of greenhouse gas (GHG) emissions from international aviation and shipping is a key priority for policymakers. The International Maritime Organization (IMO) has adopted its 2023 Greenhouse Gas Strategy and is working on the adoption of a carbon pricing instrument to decarbonize international shipping. Similarly, the European Union (EU) has extended its emission allowance trading scheme (ETS) to international shipping, while the International Civil Aviation Organization (ICAO) has adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA runs in parallel to the EU ETS to intra-EEA flights. The paper analyzes the approach taken by EU policymakers for the inclusion of aviation and shipping in the EU ETS. In particular, it discusses the regulated entities, exemptions, allowance types, geographical scope, GHG types, revenue use, fines, Monitoring Reporting and Verification (MRV) and allocation rules. By exploring the policy progress made in the two sectors and the lessons learnt from a cross-sectoral comparison of the market-based measures, this article provides valuable insights for policymakers, industry stakeholders, and other interested parties seeking to promote an effective and equitable energy transition in international aviation and shipping.

Keywords: Market-based measures · international shipping · international aviation · International Civil Aviation Organization · International Maritime Organization · EU Emission Trading System

1 Introduction

The European Union, via the EU Green Deal, envisions becoming climate-neutral by 2050. The plan includes various policy measures aimed at reducing greenhouse gas (GHG) emissions in various sectors, including aviation and shipping. Both shipping and aviation are some of the fastest-growing industries and a contributor to climate change. Thus, their decarbonisation is deemed necessary and the EU Emissions Trading Scheme (EU ETS) and Market Based Measures (MBMs) in general, among other policies, have been seen as useful components of the policy mix to address climate change.

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The EU ETS is a cap-and-trade system. From an economic perspective, it can be seen as cost-effective in theory because it creates a financial incentive for firms to reduce emissions where they are least costly. Under a carbon pricing instrument, regulated entities can choose whether to pay the price or reduce emissions—the expectation is that emissions reductions will occur only when the cost of reducing emissions is lower than the carbon price. If the carbon price is too low, it will not provide sufficient incentive for the regulated entities to have emissions reductions, and if it is too high, it could lead to economic distortions. Carbon leakage can also influence the effectiveness of the scheme. In practice, the EU ETS's actual efficiency, effectiveness, and feasibility can vary depending on its design and implementation [1]. Implementing market-based measures in the two sectors presents similar challenges due to their global nature, relevance for trade, and the existence of dedicated United Nations institutions for regulating GHGs outside the UNFCCC process. Aviation has been gaining more public attention and the altitude of where the GHGs are emitted made its decarbonisation more urgent. Therefore, EU ETS has been applied to aviation before shipping.

The paper critically examines the inclusion of aviation and shipping in the EU ETS from a policy perspective and highlights its shortcoming, but also decarbonisation potential. There is an emerging body of scholars that evaluate EU ETS from various perspectives (e.g., competition, impact on market, trading prices, policy evaluation). The originality of this paper lies in the fact that there are very few papers that examine aviation and shipping in parallel within the context of EU ETS. The lessons learned from aviation for shipping are researched [2], but this work was prior to the inclusion of shipping in EU ETS and does not include the latest developments about the aviation allowances phasing out. Our paper covers the regulated entities, exemptions, allowance types, geographical scope, GHG types, revenue use, fines, and allocation rules. Following the analysis of the EU ETS policy in aviation and shipping, the paper concludes with the key takeaways for policy makers which is also the major contribution of the paper.

2 Policy Analysis of EU Emissions Trading Scheme in Aviation

Emissions Trading Scheme (ETS) is one of the main instruments used in Europe to control GHG emissions. The inclusion of aviation in the EU ETS in 2012 (Directive 2008/101/EC) was a highly debated topic. Initially, aircraft emissions occurring within the European airspace were included in the EU ETS proposal, but after significant resistance from the international aviation community and in consideration of the International Civil Aviation Organization (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the EU decided to 'stop the clock' (Decision No. 377/2013/EU) and include only flights to and from airports located in the European Economic Area (EEA). The 'stop-the-clock' has been extended until 2026. The regulated entities, i.e. aircraft operators, are required to monitor, report and verify their emissions and to surrender allowances, i.e. permits to emit, against those emissions. When an aircraft operator does not surrender sufficient allowances to cover its emissions in the previous calendar year, an excess emissions penalty (EEP) automatically applies. The penalty is based on a price of €100/tonne of CO2 adjusted for increases in the Harmonised Index of Consumer Prices (HICP) since 2012.

While intra-EEA aviation emissions kept increasing, the inclusion of aviation in the EU ETS delivered 100 million tonnes of CO2 reductions/offsets between 2012 and 2018. There are two main types of allowances under the EU ETS, EU Al-lowances (EUAs) and European Aviation Allowances (EUAAs). Aircraft operators were entitled to use certified emission reduction credits (CERs) up to a maximum of 1.5% of their verified emissions. CERs use has been discontinued from 2020 on-wards. Every year a number of allowances is issued. The original cap on aviation allowances was 95% of the 2004–2006 emission levels and is set at 210,349,264 allowances per year [3]. Up to 82% of these al-lowances are granted for free, while the remaining 15% and 3% are auctioned and given to fast-growing airlines and new entrants, respectively and cross-sectoral trading of allowances and banking of allowances for future use is allowed. The regulation, though, does not sufficiently consider new entrants after 2015, and those operators have to purchase all the allowances and therefore are considerably disadvantaged against longer-running airlines, causing a fair competition discourse.

The overallocation of free allowances affected the carbon prices and did not allow EU ETS to realise its full potential [3]. Since then, the EU established a Market Stability Reserve to reduce the surplus of allowances. From 2021 onwards, the cap will decrease annually through the application of a linear reduction factor (LRF), which will increase from 2.2% to 4.3% for the years 2024 to 2027, and to 4.4% starting in 2028. Additionally, a linear reduction factor of 2.2% annually is applied to the aircraft operators' allowance allocations (Directive 2018/410/EC). Moreover, the free allowances will be gradually phased out by 2026. This is particularly important considering the increase of air traffic post-COVID 19 [4–6]. Carbon leakage has not been observed as the choice of routes is driven by demand, and the environmental cost for the aircraft operators is not significant enough to make them change their origin-destination routes [7].

The EU ETS acknowledges the need for aviation decarbonisation efforts to go beyond CO_2. Two-thirds of aviation's climate impacts is attributed to non-CO_2 factors [8]. These non-CO2 emissions' climate effects vary based on altitude and meteorological conditions and are not related to the fuel consumption in a linear way. Therefore, addressing the fuel consumption does not resolve the non-CO_2 effects and they require policy control. From 2025, aircraft operators will also have to monitor, report, and verify non-CO_2 emissions. These actions will facilitate better implementation of EU ETS in aviation in terms of measuring effectiveness and align better with the Green Deal commitments.

Another important element identified is the linking of EU ETS with other policies, and the policy complementarity [3, 9]. ReFuelEU, a Sustainable Aviation Fuels (SAF) blending mandate to be implemented by 2025, is interconnected to EU ETS. While free allowances are withdrawn, EU ETS will reserve 20 million allowances worth €1.6 billion from 2024–2030 to cover the price difference between SAF and Fossil Fuel and make the transition to non-free allowances easier as aircraft operators that use SAF are not required to surrender allowances for that fuel combustion. Airlines can use SAF as offsets to fulfil their ETS (and CORSIA) obligations [10]. Moreover, 5 million allowances will be transferred to an Innovation Fund to support the commercial deployment of breakthrough innovation across the economy. EU Member States have reported using more than €46 billion or 77% of their ETS revenues for climate action over the last 8 years.

CORSIA is essentially a carbon-offsetting scheme, which allows emissions from the aviation sector to continue increasing above the baseline (2019 emissions) and foresees offsetting with credits from reductions in other sectors worldwide. CORSIA is quite different from EU ETS [11] and far less ambitious. Common rules are critical in linking MBM Schemes, and so are the relative stringency and intensity of targets [7]. CORSIA puts a lot of emphasis on carbon offsetting, a practice not significantly encouraged by EU ETS as carbon offsets are not as credible and effective in reducing emissions.

Airlines are concerned about the impact these schemes will have on their costs. According to Airlines for Europe [1], in 2019, airlines spent €950 million on ETS compliance (carbon price €25/ton). Airlines for Europe argue that the cost of compliance for the EU ETS will increase five times in size by 2025 to over €5 billion annually (carbon price €80/ton), and when CORSIA is added, the cost will be €7.6 billion in 2030 and €9 billion in 2035. This will inevitably result in an increase in airline fares but will at the same time address the incorrect pricing of not including the environmental externalities and better align with the 'polluter pays' principle and therefore make the system more efficient and effective. Another element that needs to be considered further is that the price difference of EUA prices to the excess emissions penalty is very small and the EEP should be reconsidered.

3 The Extension of the EU ETS to International Shipping

In 2023, the EU extended the EU ETS to international maritime transport as part of a reform of EU ETS undertook under the EU Green Deal framework (Directive 2023/959/EU). The revised ETS Directive provides that the EUS will cover 50% of GHG emissions released in voyages between an EU port and a third country port and 100% of emissions released between two EU ports and within EU port waters (Directive 2003/87/EC, Art 3ga.1). The obligation to surrender allowances falls onto the ship owner or the entity that has adopted the responsibility to operate the vessel instead of the ship owner, including the compliance with the Management Code for the Safe Operation of Ships and for Pollution Prevention, these could be, for instance, the ship manager or the bareboat charterer (Directive 2003/87/EC, Art. 3 and Art. 3gc). The non-compliance penalty is the same as in aviation.

The instrument is phased in between 2024 and 2026. In 2024, the obligation to surrender allowances will apply to 40% of verified emissions. This will be extended to 70% in 2025 and 100% in 2026 (Directive 2003/87/EC). The types of GHGs covered will also increase over time. Initially, the ETS will apply exclusively to CO2 emissions from shipping – which alone account for about 3–4% of EU emissions. From 2026, coverage will be extended to methane and nitrous oxide. Relatedly, MRV requirements for methane and nitrous oxide will apply from 2024 onwards (Regulation (EU) 2023/957). Including methane is important to disincentivize the uptake of LNG-fueled vessels, thereby reducing risks of carbon lock-in [12]. However, these incentives are limited because the ETS will apply exclusively to GHG emissions released in using fuels on vessels, and a significant share of GHG emissions from LNG occur upstream in the production and distribution of this fuel [13].

Addressing potential risks of carbon leakage has been one of the main concerns in expanding the EU ETS to shipping, as there are several strategies that vessels could put in place to avoid or evade the carbon price [14]. Empirical simulations indicate that such strategies could become profitable for shipping companies at ETS allowances price levels well below current ETS prices [15]. Historically, carbon leakage risks under the EU ETS have been addressed primarily through the distribution of free allowances, but EU institutions are moving away from this practice. Consistently, no free allowances will be available to shipping companies, but— as mentioned above— the instrument is phased in between 2024 and 2026. In addition, to reduce avoidance risks, calls to container transshipment ports located in third countries within 300 nautical miles from an EU port are not considered ports of call in the directive – thus, the carbon price will also apply to GHG released before and after such calls (Directive 2003/87/EC, Art. 3ga). Moreover, part of the revenues raised through the extension of the EU ETS will support the decarbonization of the shipping sector. Revenues collected through the sale of 20 million allowances will be distributed to help decarbonize the sector via the Innovation Fund. The remaining revenues will be channeled to EU Member States to support climate action domestically or abroad [16].

The EU is expected to review the application of the EU ETS to international shipping in 2028 in light of policy developments undertaken by the International Maritime Organization (IMO). In case the IMO does not adopt a global carbon pricing instrument comparable to the EU ETS and aligned with the aims of the Paris Agreement, the EU will examine the possibility of extending the EU ETS beyond the 50% of emissions released by vessels in trips between an EU port and a third-party port (Directive 2003/87/EC, Art. 3gg).

There is uncertainty on the type of GHG policies that the IMO will implement following the adoption of the *2023 IMO Strategy on Reduction of GHG Emissions from Ships* (2023 IMO GHG Strategy). According to this strategy, GHG policies to be adopted by 2025 will include 'an economic element, on the basis of a maritime GHG emissions pricing scheme'. However, it remains unclear what form and level of ambition such a pricing scheme will take. Currently there are multiple proposals by the IMO Member States and industry stakeholders, with some supporting the implementation of a carbon levy, others a feebate scheme or a reward and penalty scheme [17].

Meeting the climate targets of the 2023 IMO GHG Strategy will likely require implementing stringent GHG policies. In fact, the 2023 IMO GHG Strategy sets a target for the shipping sector to become climate neutral "by or around, i.e., close to 2050", with interim checkpoints to: i) reduce GHG emissions by at least 20% by 2030 over 2008, striving for 30% emissions reductions; ii) reduce GHG emissions by 70% by 2040—striving for 80% over 2008 levels. Large investments in green fuels and related technologies are needed to meet these targets [18] and adequate GHG policies should drive these investments [19]. However, it remains to be seen whether the IMO GHG price will be considered by EU institutions as "comparable" to the EU ETS in the 2028 assessment.

4 Key Takeaways for Policy Makers

The policy analyses above have shown that EU institutions have followed different strategies for including aviation and shipping in the EU ETS despite some similarities between the two approaches. Our analysis has produced three key policy takeaways.

First, there is convergence between the application of the EU ETS to shipping and aviation in relation to some aspects of GHG coverage. Key similarities include the initial focus on CO_2 emissions followed by a gradual expansion to other GHGs and the progressive increase of the share of allowances auctioned over time, which reaches 100% in 2026. Interestingly, however, full coverage is reached differently in the two sectors. While in aviation, this is achieved with a gradual phase-out of exemptions, in shipping, this is done by phasing in the carbon price between 2024 and 2026.

Second, in the application of the EU ETS to shipping, there has been greater attention to the needs of new entrants. As mentioned above, full auctioning of allowances is reached through two different methods in the shipping and aviation sectors. A critical advantage of the approach taken in the shipping sector is that it does not put new entrants at a disadvantage compared to incumbents, since the new entrants have the same compliance measures to the existing regulated entities. Instead, new entrants in aviation will need to purchase all the allowances, while longer-running airlines will still benefit from free allowances between 2024–2026.

Third, the policy environment has changed throughout the years, becoming more favourable for "outward looking" EU GHG policies. A crucial difference between the application of the EU ETS to aviation and shipping is that the latter also covers a share of emissions from voyages from/to outside the EU. The coverage in aviation is instead limited to intra-EEA flights, as the attempt in 2012 to cover flights beyond the EEA encountered stiff resistance. While there are various factors that can explain why the inclusion of GHG emissions from non-EU shipping voyages into the EU ETS was not followed with similar resistance, we think that a critical factor is time. The inclusion of aviation in the EU ETS occurred in a pre-Paris Agreement world, where responsibility to mitigate climate change was still understood as applying exclusively to OECD countries and economies in transition within the framework of the Kyoto Protocol. The inclusion of shipping in the EU ETS occurred a decade later. In the meantime, 195 countries have become parties to the Paris Agreement, and the IMO has adopted its strategy to reduce emissions from international shipping. These are two significant developments. The Paris Agreement states that developed countries shall take the lead in addressing climate change but adds that developing countries should also contribute to addressing it. In this context, it becomes more acceptable that the EU puts a price on GHG emissions beyond its borders. Furthermore, the adoption of the Initial IMO GHG Strategy in 2018 and its revision in 2023 have put the international shipping sector on a clear pathway to decarbonization. In this context, the sub-global climate action of the EU is only an addition to the policy mix that will drive shipping's decarbonization in the coming years.

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Decarbonize European Aviation: The DESAT Model Scenarios on Small Air Transport and Short-Distance Flights Ban

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Abstract. This paper presents the results of the application of the DESAT (Demand for European Small Air Transport) strategic model, designed to estimate the demand for SAT services operated by airplanes with a passenger capacity between 9 and 19 seats, to simulate scenarios assuming the implementation of a short haul flights ban policy. The results provided by the DESAT model include the impacts on travel times, travel costs and CO2 emissions.

Keywords: Small Air Transport · air transport demand · transport modelling · regions air connectivity

1 Introduction

The aviation sector contributed in 2019 to EU27 transport GHG emissions for about 13% [1]. Aviation was particularly affected by the COVID-19 pandemic, but the drop in emissions was temporary and the air traffic activity is not expected to return to 2019 levels until 2024 at the earliest [2]. Therefore, in line with the European Green Deal [3], aviation is asked contributing to achieve the objective of carbon-neutrality by 2050. Nevertheless, among measures to reduce aviation's emissions, in Western Europe short haul flight bans are increasingly being discussed. Since April 2022, a legal ban has already come into force in France, where airlines are no longer allowed to operate flights on French domestic routes where train or coach alternatives of 2.5 h or less exist, unless such routes are targeted at connecting passengers [4].

Thanks to technological improvements, the new propulsion systems with battery or hydrogen powered designs for small aircraft providing Small Air Transport (SAT) services have a potential to reduce life cycle GHG emissions substantially. On this ground, small Air Transport (SAT) services could not only enhance connectivity and accessibility to remote regions but help maintaining air connections while pursuing decarbonisation targets.

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This paper presents an application of the DESAT (Demand for European Small Air Transport) model to the analysis of short-haul flights ban scenarios in Europe. The paper is organized as follows. Section 2 introduces the concept of Small Air Transport and the essentials of the DESAT model. Section 3 briefly summarises the implication of short haul flight ban and explains how scenarios based on this option have been simulated using DESAT. Section 4 provides results of the simulations. Conclusions end the paper.

2 Small Air Transport and the DESAT Model

2.1 Small Air Transport

Small Air Transport (SAT) refers to fixed-wing aircraft between 4 and 19 seats [5]. SAT can be used to provide superior and personalized air transport services essentially for business trips. As for OAG Schedule Analyzer data, within Europe SAT mainly provide scheduled services on routes across geographical barriers such as sea, lakes, mountains or on routes that serve thin markets [6].

Thinking of connectivity, in perspective SAT is expected to play a pivotal role in the goal of the European Commission to ensure that 90 percent of travellers within Europe can reach their destinations within 4 h by the year 2050 [7, 8]. Aviation is often indicated as a non-environment friendly transport means because of its comparatively higher level of emissions per km than other modes like rail. Therefore, aiming at improving connectivity by means of flights is, at first sight, contradictory with decarbonization targets. Nevertheless, SAT technology is developing rapidly. Currently, SAT aircraft are being developed with fuel-efficient engines and reduced airframe weigh resulting in reduced CO2 and NOx emissions of the SAT aircraft. Not long afterwards 2030, zero-emission electric and hydrogen powered SAT aircraft are projected to be available.

The new generation of SAT aircraft can therefore open the perspective of providing connectivity without compromising the decarbonization targets. It can be noted that the claimed reduction in fuel costs and maintenance costs for the zero-emissions SAT aircraft could significantly reduce operating costs, translating into fewer passengers needed to achieve the same cost per seat. Remote areas and thin markets are currently not well connected since regular air services or (high-speed) rail require high fixed costs which cannot be recovered with a small number of passengers. Commercial viability of SAT services could therefore be a further advantage.

2.2 Outline of the DESAT Model

The DESAT model has been developed by TRT Trasporti e Territorio for the German Aerospace Center (DLR) under the scope of the European Commission's Joint Undertaking Clean Sky 2.

The DESAT model covers 30 European countries, and its zoning system includes more than 1,400 zones. Within the DESAT model, small air transport is considered one of the available modes of transport for trips between zones, in competition with conventional air services, car, train, coach and, in some circumstance, ferry. More specifically, SAT is assumed as an available alternative where some conditions apply, the most relevant one being that the distance between the origin and destination zones falls within the operating range of SAT services (e.g., currently under 600 km for most of the operating services).

The DESAT model is made of two main modules. The first module deals with the estimation of origin-destination trips by SAT services between regions located within the expected range of small aircraft. The second module deals with the estimation of trips by SAT generated by regions whose origin-destination distance is above the expected range of small aircraft and that use SAT at intermediate terminals as first or last leg of the trip.

The focus of the DESAT model is the estimation of the market share of SAT services and, to consider that the availability of SAT might affect the accessibility of some zones and change the trip patterns, the generation and distribution of trips by OD pair are endogenously estimated. The share of passengers using SAT services is estimated as result of mode choice, modelled by means of a nested logit algorithm whose utility function is based on travel cost, travel duration, convenience of the departing time and comfort. Two different demand segments are considered, business and personal trips, each one using a specific set of parameters.

Together with Eurostat and OECD database, key input data for the demand model calibration is provided by the TRUST EU wide transport network model developed by TRT and applied in many European studies [9].

A detailed description of the DESAT model and its components can be found in the paper presented by the authors to the 2023 European Transport Conference [10].

3 Short Haul Ban Scenarios

3.1 Short Haul Ban Concept and Implications

In the last 30 years, air transport has become increasingly relevant in Europe. In the year 1995, its modal share was just above 5%, while in 2019, before the COVID-19 pandemic, the share was nearly 10% [1]. The contribution of air transport to CO2 emissions has therefore become more and more relevant. Over the last years, several measures have been introduced at different levels to tackle the sector's CO2 emissions [4]. However, many stakeholders argue that additional, stronger measures would be needed to reduce the sector's own emissions. One of these measures is short haul flight bans. Regulation 1008/2008 of the European Commission [11] opened room to this measure by stating the right of Member States of limiting air traffic rights "when serious environmental problems exist", under some conditions.

The most prominent (if not the only) example of such a ban in the European context is the French decision to prohibit short-haul flights if a direct train connection with a travel time of less than 2.5 h exists on the same route. The original formulation of the French regulation was, however, changed to consider specific issues, especially the feeder role of some short haul connections to hub airports and the actual existence of non-air alternatives when this role is considered [12]. These modifications demonstrate that replacing air transport without compromising regional connectivity needs care.

3.2 Modelling Scenarios

The DESAT model has been applied to assess the effects of short haul flights ban on travel times (proxy for accessibility), travel costs (proxy for transport affordability) and CO2 emissions. Five scenarios have been implemented as summarized in Table 1. Basically, scenario 0 is a sort of reference case where SAT services enter as an alternative within a range of 1100 km. On the top of this, Scenarios 1 and 2 simulate the entry into force of a ban of flights on OD pair where rail provides connection in less than 3 or, respectively, 5 h. Scenarios 3 and 4 add the assumption that SAT services are provided by hybrid or electric aircraft and are then exempted from the ban. Furthermore, the provision of SAT services with hybrid or electric aircraft is assumed to reduce user transport cost by about 50%.

Table 1. Modelling scenarios tested with DESAT.

Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
SAT services progressively introduced since 2025 within a range of 1100 km (all scenarios)				
SAT services provided by conventional propulsion aircraft			SAT services provided by hybrid or electric aircraft	
No ban of short haul flights	Ban of short haul flights if train time is < 3 hours	Ban of short haul flights if train time is < 5 hours	Ban of short haul flights if train time is < 3 hours. Electric and hybrid aircraft exempted	Ban of short haul flights if train time is < 5 hours. Electric and hybrid aircraft exempted

4 Results of Modelling Simulation

Tables 2 and 3 below summarise the outcome of the simulation considering the three indicators mentioned above. All indicators consider only trips between NUTS3 zones (local trips are not modelled in DESAT) and are the sum across all modelled transport modes (conventional air, SAT, car, rail, coach) for the OD pairs which would be affected by the ban of flights.

Table 2 shows that, according to the simulation made by DESAT, the ban of short-haul flights in Scenario 1, when train time is lower than 3 h and SAT are included in the ban, would reduce CO2 emissions by more than 40% at the horizon of the year 2050 on the OD pairs involved in the ban where, in the reference case, air modes have a modal share. This is a significant reduction, but it should be considered that OD pairs involved include a very minor share (less than 1%) of total trips and related emissions. Therefore, the total impact on the emissions at the EU level is minor. The effect on CO2 emissions is paid by a slight increase of travel time (0.4%) while travel costs would also be reduced

(3.4%). Assuming that SAT services are operated at first by hybrid aircraft and in the long term by electric aircraft, the effect on CO2 emissions is a bit higher because some more trips would be made by this mode and would not generate any emissions. The difference is small because, even if SAT tariffs are expected to be significantly reduced thanks to lower operating costs (50% reduction of fare is assumed in the scenarios 2 and 4), the SAT modal share would remain tiny.

When the ban is set to a higher threshold, i.e. when travel time by rail is within 5 h, the effects of ban are slightly larger as more OD pairs are involved (this is why even Scenario 0 results are different for Scenarios 2 and 4 compared to 1 and 3.

Table 2. Selected outputs of modelling scenarios – year 2050 – OD involved in flight ban when rail time <3 h where air share is >0

Indicator	Scenario 0	Scenario 1	*Diff wrt Scenario 0*	Scenario 3	*Diff wrt Scenario 0*
Travel times (Million hours/year)	273.0	274.0	0.4%	273.5	0.2%
Travel costs (Million euro/year)	9,730.0	9,399.8	−3.4%	9,482.1	−2.5%
CO2 emissions (Million tonnes/year)	83.4	44.2	−47.0%	43.0	−48.4%

Table 3. Selected outputs of modelling scenarios – year 2050 – OD involved in flight ban when rail time <5 h where air share is >0

Indicator	Scenario 0	Scenario 2	*Diff wrt Scenario 0*	Scenario 4	*Diff wrt Scenario 0*
Travel times (Million hours/year)	301.7	304.0	0.7%	303.1	0.5%
Travel costs (Million euro/year)	11,295.7	10,961.2	−3.0%	11,026.7	−2.4%
CO2 emissions (Million tonnes/year)	88.8	49.1	−44.7%	47.9	−46.1%

5 Conclusions

The results presented in this paper suggest that the ban of short-haul flight can have some significant local effect, but in overall terms its contribution to the decarbonisation of transport is negligible. Since the negative impact of CO2 emissions are seen globally rather than locally, the contribution of this measure to the decarbonisation target is questionable. On the other hand, the results of DESAT suggest that removing air on OD pairs where efficient alternatives exist does not significantly worsen the transport conditions for travellers. Cost can be even lower and, on average, travel time is not really higher (because of fixed times that, for short-haul play a visible role). Third, the simulation suggests that the introduction of innovative aircraft to provide SAT services would help to reduce a bit more CO2 emissions with positive (although limited) effects on travel costs and times.

The DESAT model has been mainly designed to estimate SAT demand in competition with conventional air services, car, train, coach and ferry. Potential improvements of the model cover an enhanced representation of the aviation mode, e.g. including layover flights. The estimation of the decarbonisation impacts could also be improved considering more in details technological improvements and alternative energy mix.

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Data-Analytics Tool for Facilitating the Use and Decision Making for e-car Sharing Service

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Abstract. Towards the achievement of climate neutrality in the cities, the GHG emissions in transport are expected to be reduced by 90% until 2050, while the acceleration of the introduction of innovative mobility services enabled by digital platforms in the cities facilitate the achievement of the goal. The development of an integrated e-service for vehicle sharing would assist cities towards climate neutrality and digital transition. The integrated e-service aims to assist the management and the use of shared e-vehicles and consisted of both web service application and business intelligence platform for data analysis. Through the collection and analysis of data derived from both vehicles and rental system, the data analytics platform offers decision support tools based on machine learning algorithms.

Keywords: electromobility · car sharing · business intelligence dashboard · machine learning algorithms

1 Introduction

The European Commission has a well-defined objective of transforming Europe in the first climate neutral continent until 2050 with an intermediate target of reducing the emissions at 55% until 2030 [1]. Towards this goal 100 cities are acting as pioneer climate-neutral and smart cities, that are going to achieve climate neutrality until 2030. More than 75% of EU citizens are living in the cities, although cities occupy just 4% of the land area of Europe. In parallel, while cities are responsible for the 65% of the consumption of the world's energy and the 70% of global CO_2, the road transport accounts for 20% of the total greenhouse gas (GHG) emissions [2]. Towards the achievement of climate neutrality in the cities, the GHG emissions in transport are expected to be reduced by 90% until 2050 and the low-emission vehicles are going to be 13 million in Europe by 2025 instead of 975k today [2], while the acceleration of the introduction of innovative mobility services enabled by digital platforms in the cities facilitate the achievement of the goal.

As the car sharing systems are increasing in Europe, several studies have analyzed the socioeconomic and environmental benefits of those systems. Pinto et al. (2019) identified the value proposition of car-sharing systems, where the drivers enjoy the advantages of a

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private car but without being burdened by the expense's and obligations typically linked to car ownership [3]. The car sharing systems are linked and complementary to public transport systems, as well as to the cycling and pedestrian infrastructure and the selection of transport could be made per trip based on the traveler's preferences [4]. Studies have shown that car-sharing schemes guide to change travelers' behaviors, as the users of station-based car sharing systems are intend to travel less kilometers than their previous habits. All of that are linked with lowering of GHG emissions and noise pollution, as well as reduction of traffic congestion [5].

In Greece, only limited small scale car sharing schemes have been established based on specific private initiatives in small islands, such as Astylapea [6]. Based on all the above, two initiatives have been established in touristic islands in Greece in order to develop car-sharing systems by using data driven tools for the reduction od the private car use and its negative effect to the environment and the citizens' quality of life. This paper focuses on the data driven decision support platforms that are implementing in the frame of these two projects.

2 A Brief Description of the Two Case Studies in Touristic Islands

Rhodes is a tourist island with a population of 125,113 inhabitants and an area of 1,401 square kilometers, the third most populous island in Greece and one of the most popular tourist destinations in Greece. Corfu is located at the entrance to the Adriatic Sea, in the northern part of the Ionian Sea in the Mediterranean Sea. Corfu is also a touristic island with about 97,500 inhabitants and its area is 592 square kilometers [7]. Every year these two islands host a huge number of tourists with the seasonality of this phenomenon causing several traffic and environmental problems.

Given the high vehicle ownership ratio in these islands (about half of the population owns a car), the introduction of electric car sharing systems can reduce the traveled kilometers and as the travelled distances within the islands are short, the battery adequacy is not going to increase the driver's anxiety [8]. At the same time, as satisfying the need for environmentally friendly travel of tourists is a key element of sustainable tourism, tourist areas should adhere to these principles in order to strengthen their ecological brand and as a result increase their competitiveness in the international tourism market. In both islands the e-car sharing ventures propose a mixed business model approach; at summer season the venture targets high demand for travel by tourists and it is combined with tourist attractions and activities, while at non-touristic season, the venture targets urban activities of the inhabitants with the ambitious objective of substituting private car usage with shared vehicles.

As tourists have different transport habits comparing to permanent inhabitants [6], specific surveys have been conducted focusing on tourists and locals. In fact, three stated preference surveys and one multicriteria analysis have been conducted in order to identify the needs and preferences of the tourists and the inhabitants of these two islands for using an integrated e car-sharing system. Except for their different geographical location, the two islands have significant similarities, as they have seasonal variation with summer peaks, while at the same time both islands have large areas with strong urban centers and a high permanent population.

In both cases, the integrated e-car sharing services consisting of a sophisticated mobile application for the users (different mobile app technology provider is engaged in each island) and a data analytics platform for the systems' administrators. The data analytics platform provides real-life applications stemming from the service usage and operation, and support decision making of the service operators by using intelligent tools and techniques. The platform, alongside its daily system's operation monitoring functionalities, incorporates machine learning and intelligent algorithms, based on RNN and CNN architectures, for supporting operators to decision taking regarding the future planning and operation of the system.

3 Business Intelligence Dashboard

3.1 Historical Data Processing and Analysis Tool

This tool extracts and visualizes useful results by using descriptive statistics, through the analysis of the data produced by the system's users, rentals, vehicles, as well as charging and drop off/ pick up stations. Recent studies propose various monitoring indicators for several measures related to the system's operation. These results were discussed with the involved stakeholders the two islands and the most relevant and useful indicators were co-designed by them.

It should be noted that Diagoras project in Rhodes is focusing more on e-mobility in general, as while the main focus is on e-cars, it also includes e-bikes and e-scooters. On the other side, Erica is an e-car sharing venture only and is based on an alternative

Table 1. Indicative KPIs per category

Distance	Duration	Rentals	Revenues	Charging Stations	Pick up/ Drop off Hubs	Users	Stops
Average km/ rental	Average time/ rental	Temporal distribution of rentals	Average cost/ rental	Temporal distribution of charging sessions	Flows between hubs	Customer Conversion Rate	Vehicle stops (>10 min)
Total km/ vehicle	Total time/ vehicle	e-car usage/ e-bike usage	Total cost/ vehicle	Chargers usage within the day	Categorization	Returning Customer Percentage	
				Total energy per month	Heat map origin/destination actual trips	Customer Abandon Rate	
				Average charging time		Rentals/ user	
				Average energy consumption			

exploitation of car rental. As a consequence, the Key Performance Indicators (KPIs) related to vehicles are referred to each one of the aforementioned modes of transport.

In detail, the selected KPIs are associated with crucial parts of the rental process and the system itself. At the landing page, the administrator can have a summary of the total usage of the system in a specific timespan or at the whole timeline of the system. Indicative KPIs are the total travelled kilometres, total users, total rentals, total duration of the rentals, total revenues, total energy and Co_2 emissions and average battery consumption.

As far the system operation is concerned, the KPIs are related to specific measures categories: distance, duration, rentals, revenues, charging stations, pick up/ drop off hubs, users and stops (Table 1.).

The historical data processing and analysis tool provides valuable insights about systems penetration. The information is provided for a selected period of time, while it may concern all users or a specific category of them based on their gender and/or age. Based on the above, the system administrator can derive useful information concerning the utilization of the fleet and supporting its maintenance process. Additionally, through the tool the administrator can identify specific categories of users and develops loyalty schemes of rewarding the regular and incentivizing the inactive users to return to the system.

3.2 Planning Tool

The decision support tool facilitates both short-term and long-term planning of the system to enhance the decision-making process for administrators. In detail, the tool is based on data driven models that fuses data from different sources: a static file with information and location of the charging and parking stations of the system, a static file with location of specific identified Points of Interest and the rentals database (spatial and temporal data for start and end of a rental).

As per short-term planning, the dashboard provides information for short-term prediction of the demand for trips form each station, balancing demand and supply of vehicles and charging stations, as well as charging planning. The previous described historical data is utilized in order to train different predictive models. Based on previous studies, the most suitable algorithms for the models are the machine learning regression algorithms, e.g. Random Forests, XGBoosting and AI methods utilizing Neural Networks. The results of the short-term prediction of the demand feeds the balancing demand and supply of vehicles tool and the platform provides suggestions for moving vehicles from one station to another considering spatial and time constraints. Additionally, the algorithm uses the actual distances between the stations as derived from Google maps and Open Street Maps [7, 8]. The charging planning includes suggestions based on the usage of the vehicles, as well as the energy mix in Greece (data provided by Independent Power Transmission Operator (IPTO)) [9], for instance the system suggests to return the vehicles to charging stations in time when the energy is produced by Renewable Energy Sources instead of coal.

On the other side the long-term planning includes suggestions for spatial analysis for optimal distribution of new charging and parking stations based on the most visited areas, as well as dynamic pricing schemes for regular users or specific users' categories based on the stated preferences surveys conducted during the service development. Based on the frequent visitation of the points of interest, as well as other pints within the city, temporal visitation patterns and heatmaps are produced and the tool provides suggestions for installation of new charging and parking stations.

4 Results – Discussion

The primary objective of both projects is two-fold: a) to introduce an innovative electric shared mobility framework in touristic islands and b) to transform the two islands into Living Labs by systematically collecting and analyzing mobility data. The principal business case is to establish a quadruple helix ecosystem at each island comprising of stakeholders from mobility, electric mobility and tourism industries as well as Local Authorities, citizens, tourists and innovation community. This approach will facilitate a collective decision-making process towards climate neutrality and sustainable mobility and tourism.

Despite their similarities as outlined in the previous paragraph, the two projects have distinguished differences; DIAGORAS builds a generic context of e-mobility services within a Mobility as a Service application, while ERICA is primary dedicated to and focused on the establishment of a car sharing initiative. Exploitation wise, DIAGORAS aims at the development of a Mobility as a Service business, which integrates tourism and mobility business activities, while ERICA is based on alternative utilization of rental car fleet by a car fleet owner (AVIS in this particular case). Those differences have a significant value as they have assisted in building the overall business case from two different angles. To enhance the decision-making process, comprehensive literature reviews and stakeholders' meetings were conducted within the two islands to investigate the most appropriate metrics that should be measured. The resulting KPIs have been integrated into the business intelligence dashboards streamlining the operation and utilization of the shared e-vehicle systems. Upon the commencement of system operations, the algorithms will undergo a training process, accompanied by the necessary modifications, aiming at the enhancement of the tools' efficiency.

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Innovative E-Motor Technologies for E-Axles and E-Corners Vehicle Architectures Enabling Highly Efficient and Sustainable E-Mobility

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Abstract. The Horizon Europe projects EM-TECH and HighScape propose innovative solutions for electric traction machines and their WBG-based drives and components, to achieve higher energy efficiency, reduced volume and mass, as well as reduced cost. This paper outlines the main innovations of EM-TECH and HighScape, targeting a wide range of vehicle applications, including passenger cars and commercial vehicles. Specifically, EM-TECH deals with: i) modular designs of on-board axial flux machines (AFMs) for reducing the implementation costs of scalable centralised powertrains for electric axle (e-Axle) solutions; ii) in-wheel motors (IWMs) integrated with electric gearing, for expanding the high efficiency region of electric corner (e-Corner) powertrains; and iii) the use of permanent magnets deriving from recycling processes to improve sustainability. In parallel, HighScape targets the physical and functional integration of the

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power electronics of WBG-based traction inverters, onboard chargers, DC/DC converters, and electric drives for auxiliaries and actuators.

Keywords: in-wheel motors · axial-flux motors · electric gears · wide bandgap power electronics

1 Introduction

The Horizon Europe topics CL5–2022-D5–01-09 and CL5–2021-D5–01-02 target innovations in two key areas of next-generation electric vehicles (EVs): the advancement of electric motors (e-Motors), and the promotion of the wide bandgap (WBG) based power electronics (PE) technologies (SiC, GaN, and beyond).

Within this context, the project "Innovative e-Motor technologies covering e-Axle and e-Corner vehicle architectures for highly efficient and sustainable e-Mobility" (EM-TECH) addresses innovative machine solutions with the following main objectives: i) increasing the primary efficiency of electric traction machines, namely 35% energy loss reduction for direct drive in-wheel machines (IWMs) for electric corners (e-Corners), and 25% reduction for on-board axial flux machines (AFMs) for electric axles (e-Axles), with respect to (w.r.t.) state-of-the-art (SoA) machines, during realistic driving cycles; ii) obtaining high torque density and specific torque values (>150 Nm/L and > 50 Nm/kg) for IWMs, and high power density and specific power (>30 kW/L and 10 kW/kg for AFMs); iii) achieving production costs of < 6 Euro/kW for IWMs and 5 Euro/kW for AFMs (assuming > 100k yearly units); iv) facilitating circularity solutions with > 60% reduction in the use of rare earth resources. Concurrently, the project "High efficiency, high power density, cost effective, scalable and modular power electronics and control solutions for electric vehicles" (HighScape) aims at innovative PE solutions with the following goals: i) scalable WBG-based PE components, with so far unexplored levels of functional integration in IWMs, battery systems, and auxiliaries/chassis actuators; ii) improved power density, resulting in > 100 kW/L and > 80% reduction of component volume w.r.t. existing Si-based solutions; iii) enhanced energy efficiency (up to 99%), and thermal management of the resulting PE components; iv) > 35% production cost reduction w.r.t. the available WBG-based PE products and prototypes; v) improvements in functional safety, fault-tolerance, predictive maintenance, and electro-magnetic interference (EMI) and electro-magnetic compatibility (EMC) performance.

This paper focuses on a few highlights of the activities that EM-TECH and HighScape, sharing a significant number of consortium participants, will carry out in the next 2 years, and outlines the respective innovative solutions for e-Motors and PE.

2 Innovative e-Machine Solutions

2.1 Axial-Flux e-Motor for e-Axle Applications

Table 1 reports examples of SoA e-Motors for EVs. Axial flux configurations (Yasa, Magnax) can bring significantly higher performance in comparison to the established radial flux motor implementations currently available in the market (e.g., those of the

Volkswagen ID.3, BMW i3, and Tesla Model 3). Recent advances in AFMs have been presented in the literature [1], and further improvements have been demonstrated by the EM-TECH participants (in particular, by Vaionic Technologies) prior to the project kick-off, thanks to the proof-of-concept introduction of ground-breaking innovations, namely iron-less stators, leading to: i) the absence of iron losses, which typically dominate in driving cycles like the WLTP; ii) reduced bearing losses, because of the minimal axial forces; and iii) NVH improvements, due to the decreased torque ripple and acoustic noise. To make the baseline Vaionic AFM solution mature across various vehicle segments, the EM-TECH project will pursue four crucial improvements: i) the development of a scalable design methodology; ii) the introduction of a Halbach array permanent magnet (PM) configuration to improve the flux density; iii) the use of PMs deriving from recycling processes, and implementation of the corresponding life cycle assessment (LCA); and iv) virtual sensing of PM temperature to reduce the design and operation conservativeness. Notably, items iii) and iv) are being carried out with a methodological approach also applicable to the EM-TECH IWMs.

Table 1. Characteristics of state-of-the-art on-board e-Machines for EVs, and the proposed EM-TECH solution by Vaionic.

	VW ID.3	BMW i3	Tesla Model 3	Yasa R400 P	Magnax AXF 250	Vaionic
Topology	Radial flux	Radial flux	Radial flux	Axial flux	Axial flux	Axial flux
Iron-less stator	No	No	No	No	No	Yes
Mass (kg)	40	46 [1]	47	28	25 [1]	24
Cont. Power (kW)	60	75	100	100	n.d	250
Cont. Specific power (kW/kg)	1.5	1.6	2.1	3.5	n.d	10.4
Max. Speed (rpm)	16,000	12,000	18,000	8,000	12,000	20,000

[1] Without housing

2.2 In-Wheel Motor with e-Gear for e-Corner Applications

EM-TECH will carry out a simulation-based optimisation of the baseline L1500 motor unit by Elaphe, one of the EM-TECH participants. The IWM unit is characterised by 1500 Nm peak torque, 1670 rpm maximum speed, 45 Nm/kg specific torque, 114 kW peak power, and 3.4 kW/kg specific power. Moreover, the consortium will design an innovative system with electric gears (e-Gears) through motor's winding reconfiguration, which will significantly extend its high-efficiency operating region. Previous work by Oak Ridge National Laboratory [2] suggested a costly e-Gear solution based on five antiparallel thyristors (1600V/120A at ~ 20 € each, or 1600V/240A at ~ 40€ each). The EM-TECH 2-speed e-Gear concept exploits a mechanical switching system as working principle. This offers a feasible route to achieve the cost requirement and extend this technology through the mainstream market of automotive applications. One of the key challenges in the mechanical design will be to achieve low electrical resistance between the switch contacts, without excessive mechanical clamping force. As well as traditional flat contacts, a variety of alternative solutions will be investigated, including conical contacts and lamellar contacts. The electric gearshift will unavoidably add cost to the system if all other parts remain unchanged. However, by developing and demonstrating a mechanical solution with a single actuator, it is expected that the cost will be considerably less than that of alternative solutions, such as solid-state semiconductor implementations or 2-speed mechanical transmissions. In contrast, the mechanical switching setup uses widely available materials and inexpensive manufacturing techniques. Thus, it has excellent potential for cost optimisation, either by downsizing the machine, which reduces usage of high-value magnetic materials, or by downgrading the PE in the inverter to lower current ratings.

2.3 Direct Cooling and Virtual Sensing

In EM-TECH, disruptive e-Motor improvements will be achieved through multiple solutions based on direct liquid cooling slots in the stator lamination, cooling slot channels, and wet stator cooling. Each of them has a strong impact on the mechanical layout, packaging, and manufacturing process of the machine. Concurrently with the hardware optimisation, real-time measurements and estimates of key electrical and mechanical quantities, i.e., voltage commands, phase currents and DC-link voltage signals, back EMF (electromotive force), torque and speed, together with the temperatures in key stator locations, will be used for the real-time prediction and monitoring of the temperature distribution within the PMs. In this area, past research efforts have been focusing on state observers. To overcome the drawbacks of model-based techniques, in EM-TECH novel artificial-intelligence (AI) based approaches will be developed and implemented, to guarantee fast execution times and adaptability to multiple input signal combinations. Unsupervised and supervised learning will be compared to yield robust solutions able to respond to variable working conditions, including transients of the electrical, mechanical and thermal variables. At the same time, EM-TECH will address the efficient integration of these algorithms onto conventional digital signal processors for motor control.

3 Innovative PE Solutions

The HighScape architectural solution only includes two or four IWMs (depending on the two- or four-wheel-drive nature of the specific EV) and an integrated high voltage (HV) battery, i.e., all PE components are physically incorporated into these two major building blocks (with the potential exception of the filter towards the grid), at a level never seen in any previous EV implementation. Also, from a functional perspective, the PE parts are used for multiple purposes whenever possible, across the IWMs and HV battery, with major benefits in terms of cost as well as power density and specific power, since the "overhead" parts disappear. Figure 1 a) is the schematic of the HighScape PE concept. The on-board charger (OBC), traction inverter and accessory DC/DC converter will be functionally integrated, with significant cost reduction and major power density increase, thanks to a substantial reduction of the number of components, and the replacement of the Si-based power modules with the WBG equivalents (SiC and/or. GaN), enabling higher switching frequencies and temperatures. The galvanically isolated integrated OBC will be implemented by using the SiC power MOSFETs of one of the traction drives, with the coils of one of the IWMs that are "re-used" as boost inductors. The dual-active full-bridge converter is placed within the battery, as this is the converter that adapts the voltage and current needed to charge the battery from the DC voltage created by the PFC (power factor conversion) circuit, which consists of the traction drive components. The transformer of the high voltage converter will be designed to also enable a conversion to a much lower voltage, and create the charger function for the 12V battery and accessory circuits. The EMI filters for the grid inlet, 3-phase or 1-phase, will be placed close together to enhance the system packaging. The traction motor will have the inverter as well as the PFC circuit of the OBC incorporated in some of the existing cavities in the IWM housing, while all the other PE components will be incorporated in the battery pack. Figure 1 b), c) and d) illustrate three operating modes of the highly integrated PE systems: battery charging, traction mode, and vehicle-to-grid connection.

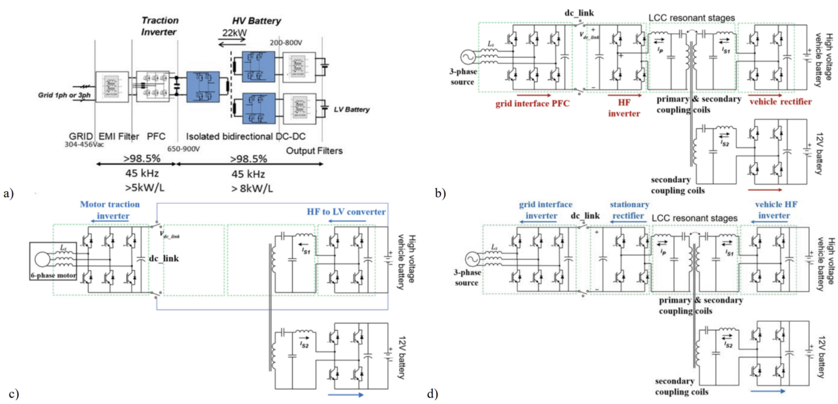

Fig. 1. The HighScape integrated PE architecture concept (a), with three operating modes (b-d).

4 Vehicle Level Control Functions

Given the absence of the drivetrain torsional dynamics and mechanical plays, direct drive IWMs can provide significantly higher wheel torque responsiveness and bandwidth than typical on-board powertrains, as well as more accurate wheel torque actuation. It is estimated that the new IWM drives will have a rise time of less than 10 ms for a step torque demand. This will be exploited for new control functions at the vehicle level. For example, the new IWMs will provide faster dynamic response than conventional friction brake actuators, and therefore could be adopted for anti-lock braking system (ABS) torque modulation. During ABS events, the friction brakes would provide only the low-frequency component of the braking torque. This idea has been mentioned and preliminarily assessed in a proof-of-concept analysis by Toyota [3], but it has never been systematically implemented, also for the lack of IWMs meeting the industrialisation requirements for passenger cars, which will be covered by EM-TECH and HighScape. Similar benefits could be achieved during traction control operation. In parallel, tyre-road friction preview for wheel slip control, which could be achieved through future vehicle-to-everything (V2X) implementations, will be evaluated, according to the initial promising study in [4], focused on sudden variations of the friction coefficient during longitudinal acceleration tests. Fast modulation of the IWM torque can be also used to dampen the longitudinal vehicle body acceleration oscillations caused by the road irregularities, and thus improve the drivability. In this respect, a preliminary simulation study has been presented in [5]. Within HighScape and EM-TECH, a first proof-of-concept experimental implementation will be carried out.

From a methodological viewpoint, nonlinear model predictive control (MPC) solutions will be adapted to the control of the new electric drives, and expanded to include neural network (NN) technologies, which will result into neural network model predictive control. For example, the NNs will be used for capturing the nonlinear dynamics that are difficult to model analytically, e.g., the effect of the uncertain tyre-road friction coefficient. The activity will focus on: i) exploring the achievable vehicle performance impact of IWM settings with different levels of responsiveness; and ii) providing robust controllers that could be further industrialised at project completion.

5 Virtual and Experimental Testing

The EM-TECH and HighScape verification and validation environment will consist of: i) a set of models of e-Machines, powertrains and full vehicles, including real-time reduced-order models, together with a functional mock-up interface (FMI) for co-simulation; ii) connected Hardware-in-the-Loop (HiL) platforms for the assessment of motor/inverter and vehicle controllers, and other relevant controllable hardware components, including EV systems that require a joint operation with the e-Machine, e.g., for regenerative braking; and iii) dynamometric testing setups to emulate the operation of electric propulsion units in laboratory conditions under real load and speed cycles. This constellation of tools will enable flexible testing as part of a digital twin development process to perform functional and life cycle analyses of the new IWMs, AFMs, and PE components. The XiL (X-in-the-Loop) verification of the components and systems will be complemented by testing on the project EV demonstrators, represented by modified versions of production vehicles of the involved car makers (AUDI and TOFAŞ).

6 Conclusion

This paper has outlined the planned developments of the Horizon Europe EM-TECH and HighScape projects. The innovations will result in new in-wheel machines with so far unexplored levels of torque density and specific torque ($>$150 Nm/L, $>$ 50 Nm/kg), and on-board axial flux machines with high power density and specific power ($>$30 kW/L, $>$ 10 kW/kg). Both machine technologies will be characterised by significant reductions of the energy losses and their rare earth content. As a result, it will be possible to reach the competitive production costs of $<$ 6 Euro/kW for IWMs and 5 Euro/kW for AFMs, for yearly volumes $>$ 100k units. For the new WBG-based traction inverter solutions, $>$ 80% size reduction and $>$ 60% average power loss decreases w.r.t. Si-based solutions are expected.

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Markov Chain and K-means Clustering Analyses for Constructing Electric Vehicle Drive Cycles for Dublin, Ireland

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Abstract. This paper presents a comparative analysis of Markov chain and K-means clustering techniques for constructing representative drive cycles in the optimisation of powertrain modules for electric vehicles (EVs). As part of the EU funded POWERDRIVE (Power electronics optimisation for next generation electric vehicle components) project, the research focuses on a case study conducted in Dublin, Ireland, aiming to develop an accurate and efficient drive cycle that captures the unique driving patterns and characteristics of the city. The Markov chain technique utilises historical driving data to model the transition probabilities between different driving states, while the K-means clustering technique groups similar driving patterns based on key parameters. The analysis evaluates the effectiveness of both approaches in terms of their ability to accurately represent real-world driving behaviour and their computational efficiency. The results of the study provide insights into the strengths and limitations of each technique, enabling researchers and practitioners to make informed decisions when selecting an appropriate methodology for drive cycle construction. The findings contribute to the ongoing efforts in developing optimised powertrain modules for EVs and advancing the field of electric vehicle technology.

Keywords: Drive cycles · Electric Vehicles · Optimisation

1 Introduction and Literature Review

A drive cycle (DC) is a set of data points that represents the driving patterns of a particular region, vehicle class, or road type. In most cases, it is a speed-time plot developed for specific conditions designed to replicate and simulate real-world driving scenarios. The DC is set as a standard to test the performance of a vehicle and its parts in measurements such as fuel consumption or battery usage [1].

In the literature, there are two major methods for constructing DCs: the microtrip (MT) method and the Markov chain Monte Carlo (MCMC) method. The MT method divides recorded trips into segments, usually the period of driving between idle periods (stops). Then, these MTs are pieced together to form a final DC [2]. The MCMC method takes changes, either between consecutive seconds or fragments, from recorded trips

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and creates a matrix of the probability of the next second's state. Then, Monte Carlo simulation is used to select the next driving state based on the Markov chain property that the state is determined only by the previous state [3]. Although no standardisation exists for the development of a DC, most DCs are created using a variation of one of these methods. Often, the DC developers give little or no justification for their chosen methodology. This leaves a question of finding the optimal state-of-the-art method to the DC developer.

Few studies have compared the merits of construction methods. The few that do are limited to one sample region and dataset [4]. These studies also must create their own algorithms and methodology for collecting the data and forming the DC. For these reasons, it is not possible to draw universal conclusions from previous studies. Both the MT and MCMC methods have been shown as more representative of real-world driving through various comparisons [4, 5]. Therefore, it is important to continue this investigation with thorough documentation of each step of the methodology.

As the field of machine learning has improved, it has become common to include some machine learning techniques in the creation of DCs. Most popular among these are the unsupervised learning algorithms of k-means clustering [6, 7] and principal component analysis [8, 9]. Clustering has many different applications in the creation of a DC, but the most common is to group MTs by certain defining parameters [6]. These are generally labelled as characteristic parameters (CPs) because they are used to evaluate driving behaviour and the representativeness of that behaviour in the final cycle. The goal, then, is to ensure that the variety of behaviour across trips can be represented fairly in the DC.

2 Methodology

2.1 Data Collection and Processing

Most of the literature on DCs seeks to create a DC representative of the study region. Instead, this study focuses solely on comparing two construction methods. To achieve this, two electric vehicles, a Hyundai Kona and a Nissan Leaf, were fitted with a data collection device. Both cars operated in Dublin's urban areas during weekday commutes and in suburban areas during weekends. The vehicles were equipped with an OBDLink MX + device that paired with the Car Scanner ELM OBD2 app on the drivers' phones. In the following sections, we will detail the process of building our database, explain how we implemented the DC construction methods, and describe the methodology employed to evaluate the representativeness of the obtained DCs.

The collected data consisted of 30 trips across a two-week period. During the data collection process, it was observed that the recorded data had varying frequencies, ranging from 2 to 10 Hz. To ensure consistency, the first step in data pre-processing involved aggregating the data to uniform 1 Hz intervals. This is a necessary step to shape the data into second-by-second values, which will eventually form the final DC. Unlike GPS speed values, there was no need for data denoising or filtering. The speed data, directly recorded from the vehicle, were already accurate, negating the need for additional data smoothing techniques.

Once the second-by-second data frame was created, there were a few seconds with no speed values due to the inconsistency of the collection process. To address missing values within the dataset, a 3-point moving average method was employed. Additionally, trips that commenced or concluded at speeds other than 0 were manually excluded from the analysis [5]. Trips like these indicated a failure of the data collection process or the driver stopped the process intentionally for privacy or other reasons. This filtering process resulted in a final dataset consisting of 26 trips, covering a total distance of 1501.8 kms. Then, the data was ready to be constructed into a DC by the MT and MCMC methods using algorithms displayed in Fig. 1.

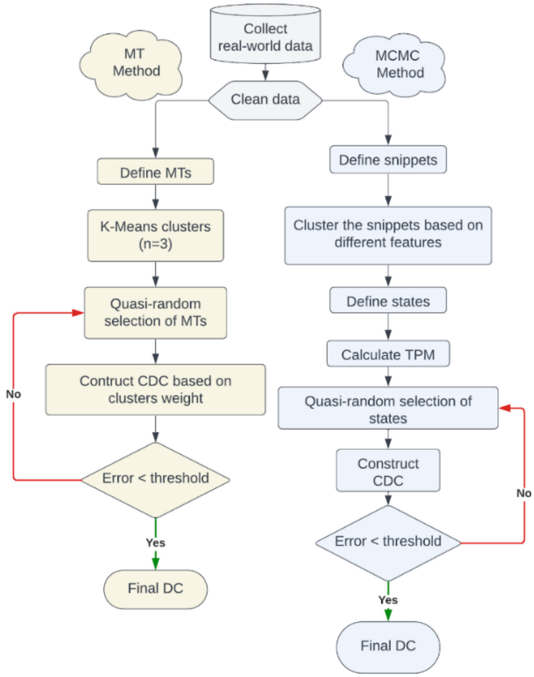


Fig. 1. Flowchart of the algorithm for each method to create a drive cycle.

2.2 Microtrip Method with K-Means Clustering

The first step and distinguishing feature of the MT method for constructing DCs is dividing the trips into smaller segments called MTs. These MTs are meant to act as building blocks for a DC that capture driving behaviour. Then, the MTs can be pieced together, making sure the resultant DC contains an adequate representation of behaviour through CPs. The most commonly used definition of MTs is the sequence between two consecutive zero-speed intervals, so this is how the study divided MT [10].

Because this study examines the most common cycle construction techniques, MTs were divided based on consecutive stops. A total of 267 MTs were extracted from the cleaned data. Each MT was characterised based on the average speed, average acceleration, and average deceleration during the MT. These 3 dimensions were then clustered using k-means clustering algorithm with k = 3. The clusters are shown in Fig. 2. The MTs were then quasi-randomly selected based on the weighted proportion of each cluster. MTs were added until the DC reached or passed the target duration of 1500 s. Ten thousand candidate drive cycles (CDCs) were created iteratively. The final DC was then chosen as the CDC with the least relative error in drive mode: percentage idling, accelerating, cruising, and decelerating values.

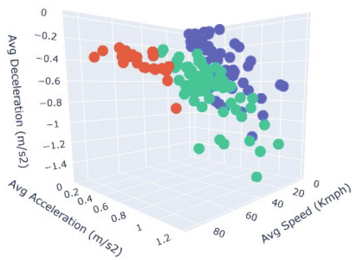


Fig. 2. Results of k-means clustering.

2.3 Markov Chain Monte Carlo Method

For the MCMC method, the data was first segmented into small snippets, where a snippet was defined as the speed profile between two consecutive 0.5 km/hr speed values. The percentage of accelerating, decelerating, cruising and idling values were calculated for each snippet (referred to as features in Fig. 1). The snippets were then clustered using k-means clustering (k = 7) based on these drive mode percentages. Then, a transition probability matrix (TPM) was constructed by calculating how often each cluster was succeeded by another in the dataset.

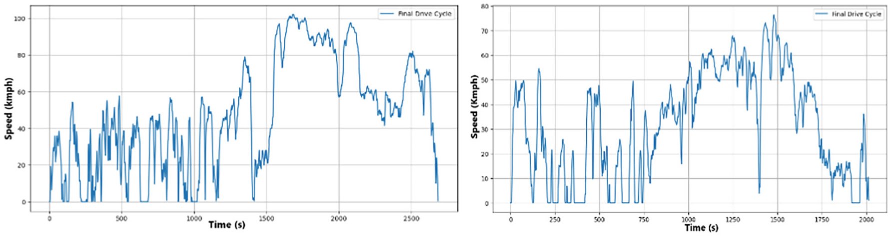
Following the construction of the TPM, the Monte Carlo method was employed to select driving snippets from real-world driving data, which together constitute the CDCs. To elaborate, once the initial state *i* is established, a random number s is generated within the range of [0,1]. Subsequently, s is compared to the cumulative state transition probability associated with state *i*. If s satisfies the following condition:

$$\sum_{j=0}^{k} P_{ij} < s < \sum_{j=0}^{k+1} P_{ij} \quad (1)$$

k + 1 is selected as the next state and a snippet from that cluster is added. The process was repeated until the desired duration of the cycle was reached or crossed, again at 1500 s. CDCs were created until a relative error threshold was reached.

3 Results and Discussion

The major differences between the MCMC method and the MT method used in this study are the division of trips into segments of different lengths, clustering around different CPs, and the method of selecting consecutive segments for the CDC. All three of these nuances result in a different way to communicate driving behaviour through the final DC. Figure 3 displays a visual comparison of the driving behaviour through the selected DCs from the MT method (Fig. 3a, left) and the MCMC method (Fig. 3b, right).



(a) (b)

Fig. 3. Final drive cycles for a) MT method (left) b) MCMC method (right)

These DCs were chosen because they had the closest match of CPs to real-world data from among the created CDCs. However, there are many parameters considered and each cycle may be better at representing certain behaviour than the other. A total of 17 CPs were considered to compare the DCs, shown in Table 1.

To gauge the representativeness of the cycles, we utilize RMSRE (Root Mean Square Relative Error), which can be computed using the following formula:

$$\mathrm{RMSRE} = \sqrt{{}^{1}/_{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} \left(\frac{\mathrm{P_i} - \mathrm{P_{Ri}}}{\mathrm{P_{Ri}}} \right)^2} \tag{2}$$

where, P_i represents the i_{th} parameter of the constructed drive cycle (MT or MCMC), P_{Ri} stands for the i_{th} parameter of real-world data, and N denotes the total number of parameters. As per Eq. (2), the RMSE for MT and MCMC in comparison to real-world driving data is 19.9% and 20.1%, respectively. Overall, the MT method replicates the driving behaviour captured by these CPs much better than the MCMC method.

Table 1. Characteristic Parameters of Data and Drive Cycles.

Parameter	Real-world data	MT method (% error)	MCMC method (% error)
Percent Driving Time (%)	93.83	94.08 (0.27%)	94.84 (1.08%)
Percent Acceleration Time (%)	26.79	26.85 (0.22%)	24.01 (10.38%)
Percent Deceleration Time (%)	25.15	24.95 (0.8%)	24.65 (1.99%)
Percent Cruising Time (%)	42.16	42.46 (0.71%)	44.39 (5.29%)
Percent Idle Time (%)	5.9	5.73 (2.88%)	5.16 (12.54%)
Maximum Speed (Km/hr)	135	102 (24.44%)	123.7 (8.37%)
Mean Speed (Km/hr)	49.6	47.63 (3.97%)	63.07 (27.16%)
Mean Running Speed (Km/hr)	52.71	50.53 (4.14%)	68.33 (29.63%)
Standard Deviation of Speed (Km/hr)	29.9	29.72 (0.6%)	33.45 (11.87%)
Maximum Acceleration (m/s^2)	7.27	2.78 (61.76%)	3.31 (54.47%)
Mean Acceleration (m/s^2)	0.26	0.27 (3.85%)	0.28 (7.69%)
Maximum Deceleration (m/s^2)	− 5.37	− 2.9 (46%)	− 3.83 (28.68%)
Mean Deceleration (m/s^2)	− 0.43	− 0.48 (11.63%)	− 0.37 (13.95%)
Standard Deviation of Accel (m/s^2)	0.54	0.55 (1.85%)	0.53 (1.85%)
Standard Deviation of Decel (m/s^2)	0.46	0.46 (0%)	0.46 (0%)
Root Mean Square of Accel (m/s^2)	0.54	0.55 (1.85%)	0.53 (1.85%)
Root Mean Square of Speed (Km/hr)	57.92	56.14 (3.07%)	71.39 (23.26%)

4 Conclusion

The results of this study show how the complex construction methods can lead to certain desired effects in the final DC. For instance, the MT method does a better overall job at matching real-world CPs, but it gives larger errors in CPs such as maximum speed and acceleration because it only incorporates a small fraction of the total driving behaviour.

The MCMC method, meanwhile, has a slightly larger RMSRE and less accurate drive mode percentages despite the k-means clustering algorithm being specifically applied to those CPs. Ultimately, the constructors of a DC have a lot of choice in the methods utilized to create a DC. The results of this study show that the chosen method can have a significant effect on the way driving behaviour is captured through a DC, so the methods must be chosen carefully.

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Examining How Geographical Location Impacts Fuel Cell Electric Bus Operational Energy Consumption and Carbon Emissions

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Abstract. This paper examines the impact of geographical location on the energy consumption of double deck fuel cell electric buses operating in two UK cities. By considering seasonal variation in ambient temperature, the implications on operational carbon emissions were investigated. Using a MATLAB/Simulink model the total energy demand of a vehicle operating on the UK Bus Cycle was simulated. Results show that the range of a fuel cell electric bus can reduce by 18.3% due to seasonal and geographical ambient temperature variations. The carbon emissions associated with refuelling can change by up to 17% between summer and winter and are 20 times higher when hydrogen is produced by electrolysis using grid electricity compared to renewable electricity.

Keywords: Fuel call electric bus · vehicle modelling · carbon dioxide emissions

1 Introduction

In the UK, the transport sector is the largest single contributing sector to greenhouse gas emissions (responsible for 27% of emissions in 2019) [1]. Public transport will play a large part in meeting net zero targets in the transport sector. However, there are several challenges which need to be overcome to establish fully zero emission bus fleets, both within the UK and globally. Over the past twenty years, there have been significant shifts in the powertrain technologies utilized and there are numerous low and ultra-low emission powertrain technologies in operation on the roads globally. However, within the UK diesel/diesel hybrid bus technologies are the dominant power topologies entering into service – in 2021, 86.1% of new buses and coaches registered were diesel/ diesel-hybrid, compared to 11.9%, battery electric, 0.4% fuel cell electric and approximately 1.6% petrol or gas. [2].

Hydrogen fuel cells convert the chemical energy of stored pressurized hydrogen gas into electrical energy which is then used to power the drive train. Fuel cells require extremely high levels of hydrogen purity (99.97%) with any contaminates negatively impacting performance and lifetime.

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The operational energy consumption of hydrogen fuel buses has been approximated via rule of thumb or physics-based simulation methods previously within the literature. Rule of thumb estimations, where an average energy consumption (kg/km or kWh/km) is combined with the distance to estimate route level consumption, have been used commonly within environmental [3] and economic assessments [4] with values of 1.8 kWh/km [3] and 10 kg/100 km [4] used previously.

Previous physics based models have included work undertaken by [5], which estimated energy consumption of a double deck hydrogen fuel cell bus operating on four industry standard synthetic drive cycles, with an average consumption value of 6.17 kg/100 km. Another study [6] undertook analysis to identify the factors impacting performance of a single deck bus, as well as assessing sensitivity of passenger loadings on six different powertrains. The hydrogen fuel cell was found to have second lowest energy consumption of the simulated vehicles, with a mean value of 1.849 kWh/km and a standard deviation of 0.069. These previous studies have shown that there is large uncertainty associated with operational energy consumption values, with no studies examining the influence of geographical location and ambient weather condition.

Whilst hydrogen is considered zero emission at point of use, with heat and water the only emissions, the environmental impact of the bus operation depends on the hydrogen production pathway. Subsequent storage, transmission and distribution will also result in additional energy requirements and associated emissions. A UK based well-to-tank analysis calculated the greenhouse gas emissions of six production pathways, three distribution pathways and two dispensing options (a total of 32 scenarios) [7] and established that hydrogen produced via renewables based electrolysis represented one of the lowest emission pathways. This analysis has been used as the basis for estimating emissions for certifying buses in the UK with zero emission status [8] with values of 7.2 $kgCO_{2e}$/kg and 139.9 $kgCO_{2e}$/kg reported for hydrogen produced via grid electricity and renewable electricity sources respectively. A review of 99 life cycle assessments on a range production methods reported values of between 0 – 12.5 $kgCO_{2e}$/kg for hydrogen produced by electrolysis using renewable energy sources [9]. With ongoing commitments by transport operators and plans to achieve net zero, assessing the impact of geographical location and variations in ambient temperature in terms of operational energy consumption and carbon emissions is essential to ensure well informed decision-making in regard to fleet wide decarbonisation.

2 Methodology

2.1 Fuel Cell Electric Vehicle Modelling

A fuel cell electric bus vehicle simulation model (Fig. 1) was developed to predict energy requirements of both the powertrain and associated HVAC loads for different operational scenarios. The modelling approach and strategy, as well as the governing equations, used in this work are documented by [10].

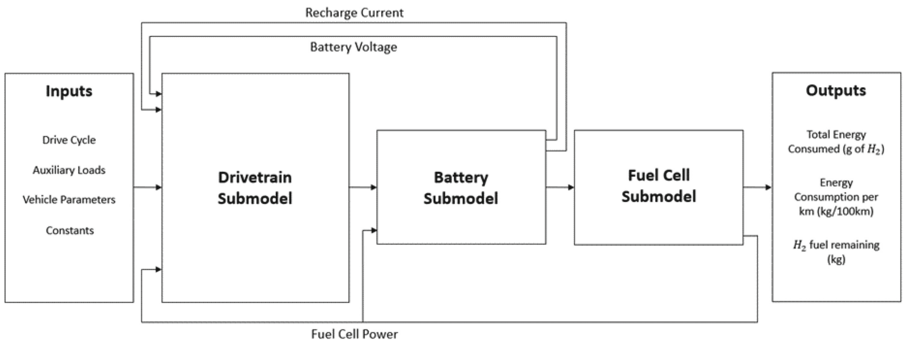

Fig. 1. Schematic of Fuel Cell Electric Vehicle Simulation including model inputs and outputs.

2.2 Vehicle Operating Conditions

The bus considered in this study was assumed to have a 4 × 2 configuration with a medium duty electric motor. The powertrain consists of a 70 kW fuel cell stack as the primary power source, a 27 kWh lithium titanate battery designed to absorb energy from regenerative breaking with a 25 kg hydrogen fuel tank. Operating conditions were based on the Zero Emission Bus scheme certification criteria [11]. Assuming a vehicle kerb weight of 14,300 kg and 50% seated capacity, the bus was assumed to have a constant test mass of 16,900 kg throughout all simulations. The bus was assumed to have frontal area of 10.269 m^2, drag coefficient of 0.6, rolling resistance of 0.007, and operating with 4.7 kW auxiliary load.

Average temperature distribution data was compiled for Aberdeen and London in the UK. The data was collected from weather stations for the period of 2011–2021 [12] and is summarized in Table 1. To assess the impact on vehicle's energy consumption as a result of decreased/increased HVAC loads, seasonal average ambient temperature profiles were used for each location.

Table 1. Average ambient temperatures per season for study locations (lat/long) and associated heat load.

	Aberdeen, Scotland (57.205, -2.205)		London, England (51.482, -0.294)	
	Temperature (°C)	Heat load (kW)	Temperature (°C)	Heat load (kW)
Spring	7.6	2.653	10.2	1.698
Summer	13.6	1.175	17.5	0.000
Autumn	9.6	1.871	11.8	1.389
Winter	4.4	4.086	6.1	3.346

A duty cycle consisting of 16 repeated runs of the UK Bus Cycle (UKBC) drive cycle was created for both locations (13.9 h, 262 km), the same as that used in [10]. As the same duty cycle was assumed for each city, the difference in energy consumption due to regional temperature variation was attributed to the auxiliary heating load. The average heating load for each of the ambient temperature conditions was calculated over the duration of the duty cycle using an updated double decker version of the Recovery Heat Pump model developed by [13] for an internal saloon target temperature of 17 °C, as specified by the ZEB certification process. Table 1 shows the auxiliary heating loads required during each season for each of the locations considered in this study. To illustrate the effect that heating requirements for different ambient temperatures have on the vehicle, the simulated energy consumption and associated range are compared across all seasons for both cities.

2.3 Hydrogen Production Pathways

Within this paper two hydrogen production pathways are considered, which are based on the values used by when certifying UK ZEB status [8]. The first production pathway is based on production via electrolysis using UK grid electricity, assuming compressed gas delivery of 200 km and dispensing at 350 bar with a carbon factor 139.95 gCO_{2e} /MJ. The second production pathway is production via electrolysis using renewable electricity, assuming compressed gas delivery of 200 km and dispensing at 350 bar with a carbon factor of 7.22 gCO_{2e} /MJ.

3 Results

3.1 Fuel Cell Electric Vehicle Modelling – Sensitivity to Seasonal HVAC Loads

To assess the impact of geographical temperature variations the energy consumptions and the corresponding maximum ranges of the FCEB are shown in Fig. 2. Unsurprisingly, the highest energy consumption occurs in winter when the ambient temperature is at its lowest and heating requirements are greatest, and the lowest in summer when the heating requirements are lowest due to the ambient temperatures being highest. What is of interest is the differences incurred due to the city location.

The predicted operating range can be reduced by up to 72 km, a percentage decrease of 18.3%, depending on the ambient temperatures in the study locations. London was found to be the city with the largest range variation between seasons, with a difference of 61 km expected between summer and winter. Summer shows the largest variation within individual seasons, with a 24 km difference in range between London and Aberdeen. This is due to the 3.9 °C average summer temperature difference.

Figure 2 also shows the carbon emissions of operating the vehicle in Aberdeen and London, based on two hydrogen production pathways (electrolysis via UK grid or renewable energy), with carbon emissions from hydrogen produced via grid electricity more than 20 times higher than production via renewable energy sources. Within the cities carbon emission varied seasonally, with a 14% and 17% difference between summer and winter in Aberdeen and London respectively.

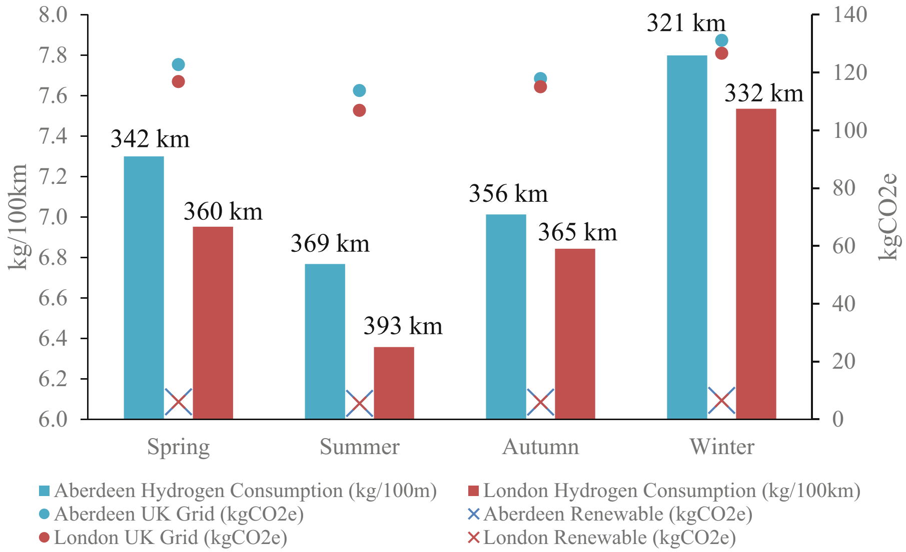

Fig. 2. Energy consumptions and carbon emissions for each study location and season.

4 Conclusions

This study has shown the importance of considering the geographical and seasonal ambient temperature variations when operating a fuel cell electric vehicle. Based on modelling undertaken for the cities of Aberdeen and London, the range of the same generic double deck FCEB can reduce by 18.3% (72 km) due to the changing heating requirements based on the ambient temperature. Carbon emissions associated with hydrogen refuelling follow the same trends, varying seasonally within each city, with up to 17% difference between summer and winter seen in Aberdeen due to the change in ambient temperature. Carbon emissions were shown to be 20 times higher with hydrogen produced using grid electricity compared to renewable electricity.

The significant range and carbon emission difference depending on the regional and seasonal energy consumptions highlights the challenges that policy makers and bus operators face when transitioning from more conventional diesel to zero emission bus fleets. Scheduling of the bus fleet services will be more complex as temperature variations impact range, and optimised heating strategies with adaptive internal set point temperatures, and heat recovery from fuel cell systems to offset HVAC loads could offer energy savings. A hydrogen production strategy using renewable energy sources for electricity must also be in place in order to reduce the carbon emissions associated with refuelling FCEBs.

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The Orcelle Project – Towards Wind-Powered Ships for Deep Sea Cargo Transport

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Abstract. International regulations on greenhouse gas (GHG) emissions as well as strong market demand for zero-emission transport calls for a radical change in the shipping industry. Measures such as hull form optimization, use of alternative fuels and efficient machinery systems, new coatings, and smart routing have already improved the energy efficiency of the world fleet. However, it is far from enough. To effectively respond to the climate challenges, we must turn to *emission-free energy sources*. One such promising and well-proven zero-emission propulsion system for shipping is wind propulsion. Using wind to power cargo vessels re-started on a commercial scale about a decade ago and there are today more than 50 wind-assisted vessels in commercial trade or under construction. They are equipped with a variety of wind propulsion technologies like Flettner rotors, wing sails and kites, which may give fuel and emission reductions of up to about 20%. With the goal of demonstrating that even higher energy and emission reduction is feasible, 11 representatives of the European maritime industry and research community have recently joined forces in the large-scale EU-funded project Orcelle, led by Wallenius Wilhelmsen Ocean. The present paper outlines the project's ambition, scope of work and expected outcome.

Keywords: Wind Propulsion · GHG Reduction · Wing Sails · Decarbonization

1 Introduction

In alignment with the emission reduction goals set out in the United Nation's 2015 Paris Agreement, the International Maritime Organisation agreed recently on a revised plan to reduce the total annual greenhouse gas (GHG) emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008; and by at least 70%, striving for 80%, by 2040, compared to 2008; and CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008

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(IMO-MEPC90, July 2023). These international regulations, as well as strong demand from the market, call for radical innovations in the frame of zero-emission maritime technology and shipping.

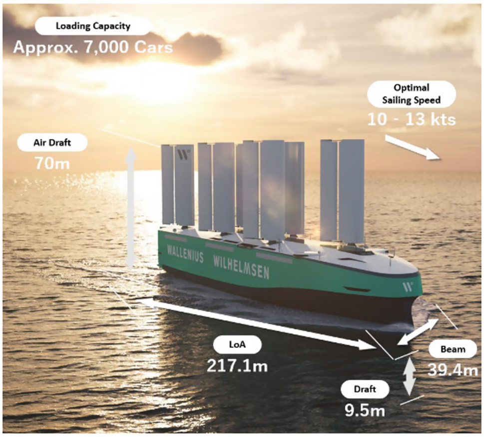

Fig. 1. The Orcelle demonstrator (reproduced with permission from Wallenius Marine, copyright Wallenius Marine, 2024)

Various solutions are currently discussed in the maritime transport sector. Among others, Bouman et. al. (2017) have studied the CO_2 reduction potential of various improvement measures such as hull design, power & propulsion system, alternative fuels, alternative energy sources and operational measures. Out of many possibly viable solutions, a promising and well-proven solution with good market potential is *wind propulsion* (Nelissen et.al. 2016).

Using wind to power cargo vessels re-started on a commercial scale about a decade ago. Currently, there are about 50 wind-assisted vessels in commercial trade and/or under construction (EMSA 2023). The main implementations in practice are so far:

- *Flettner rotors*: E-Ship 1 (RoRo), Maersk Pelican (tanker), Fehn Pollux (general cargo), Annika Braren (general cargo) and Copenhagen (ferry). Rotors were recently also fitted to deep-sea ships: Sea Zhoushan (Bulk) and Sea Connector (RoRo).
- *Wing sails* (e.g., Ayro of OceanWings, WindWings of BARTech / Yara Marine, Wisamo inflatable sails by Michelin, OceanBird of Alfawall, advanced in the Orcelle project). Among the prototypes with wing sails, as of today, is the 121m long Ro-Ro cargo ship Canopée, delivered in December 2022. Its hybrid propulsion uses a combination of wing sails of Oceanwing type and traditional engines. Also, in late 2022, the VLCC New Aden was delivered to China Merchant Energy Shipping, built by Dalian Shipbuilding Industry Co; it is equipped with two pairs of new generation rigid wing sails.
- *Suction wings*; Ankie (general cargo), Frisian Sea (general cargo), and La Naumon (general cargo).
- *Soft sails*: Neoline (RoRo) and *kites* Beluga (Container), AirSea (RoRo) are less common and may have limited impact.

The wind propulsion systems, currently in use, deliver fuel reductions of up to (at best) 20% by assisting ship's main propulsion engine, which is in general a diesel or LNG fueled engine (hybrid WASP: Wind Assisted Ship Propulsion systems). These are partly significant savings, but far from enough to reach the international GHG emission targets. There are a few built ships with wind as the *main propulsion*, in the segment of private yachts and very exclusive cruisers, but not yet any large vessels for deep-sea cargo transport driven primarily by wind.

With the goal of demonstrating that a drastic reduction of emissions from deep-sea cargo transport is possible, 11 representatives of the European maritime industry and research community have recently joined forces in the EU-funded project Orcelle (2023–2027). The consortium is led by Wallenius Wilhelmsen Ocean and includes Wallenius Marine, AlfaWall Oceanbird, RISE SSPA Maritime Centre, Royal Institute of Technology, StormGeo, National Technical University of Athens NTUA, DNV, Ghent University, Volvo Cars, and Maritime Cleantech. The efforts aim to advance several technologies from Technology Readiness Levels TRL3–4 to TRL7, including the wing system and ship design, as well as the simulation platform, safety regulation framework, business models and weather routing software. The advance of generated know-how will be demonstrated by two physical demonstrators, a retrofitted vehicles carrier (*MS Tirranna*, IMO: 9377523) and a newbuilding car-carrier, both of Wallenius Willemsen. The present paper outlines briefly the Orcelle project's background, ambition, scope of work and expected outcome. For a more detailed description of the project, see Werner et al. (2023).

2 The Orcelle Concept

The goal of the consortium's efforts is to build and start operations of a wind powered car carrier, namely Orcelle. The concept design of the planned ship is already mature through background research and development work in earlier collaboration between the project partners. The concept vessel of Ro-Ro car carrier type, measures 232 m in length, 40 m in beam and has the capacity to load approximately 7,000 cars or equivalent cargo. The optimal sailing speed with wind is predicted to be between 10–14 knots. The vessel size and capacity are chosen in relation to the identified transport route and cargo flows. The evaluation of energy efficiency has been performed for two different routes, a trans-Atlantic and a trans-Pacific route. The Atlantic route includes major ports on the EU-side, e.g., Zeebrugge and Bremerhaven, and Halifax and New York on the US east coast side. The trans-Pacific route includes ports in east-Asia e.g., Ulsan and Pyeongtaek and San Diego and Port Hueneme on the US west coast side. The great circle round-trip distances are 7.000 and 11.500 nautical miles for the trans-Atlantic and trans-Pacific routes, respectively.

The ambitious energy savings target is + 50% for a year-round service. This has been determined by simulations on the basis of statistical weather data and applications of the employed simulation tools, developed by the consortium partners in the background research project "Wind Powered Vehicle Carrier", funded by the Swedish Transport Agency. The simulation tools platform comprises several modules and some main features of the simulation platform are briefly described in the following.

Hydro and Aero Modeling. Hydrodynamic modelling and analysis of the vessel hull, while experiencing large leeway angles and variable propeller load, is based on CFD (3D RANS). The employed numerical method has been validated using experimental tests in the towing tank of SSPA. The aerodynamic modelling of the wings and hull topsides, the interaction between the hull and wing systems, and interaction between the different sail systems on the hull topsides is based on a multi-fidelity approach mixing 3D RANS, 2D RANS and lifting line methods (Malmek 2020). Examples from the aerodynamic modeling are shown in Fig. 2. The method has been validated using wind tunnel tests at SSPA (Marimon et al. 2022).

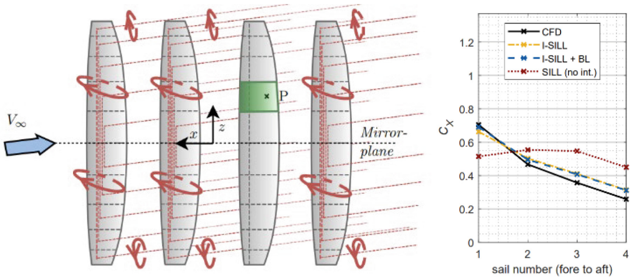

Fig. 2. Aero modelling examples and Multifidelity method (I-SILL) (Malmek, 2020).

Velocity Prediction. A velocity prediction program VPP has been developed, where the non-linear systems of constrained force and moment equilibrium equations of the vessel system are solved to provide a large range of performance parameters given certain wind and wave conditions (Olsson et al. 2020).

Routing. An optimal routing methodology, which enables the operational energy savings to be assessed on various trading routes across the globe, has been developed. The methodology considers the need for the vessel to fit into a logistics system regarding arrival time and lateness and considers ECMWF (European Centre for Medium-Range Weather Forecasts) weather data captured during the last decade (Fig. 3).

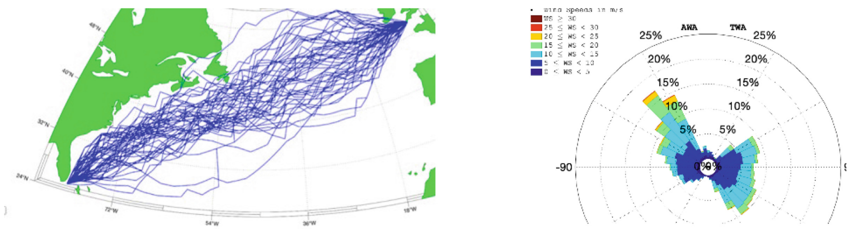

Fig. 3. Results from UK to NY routing simulations with wind statistics (Werner et al. 2021) (reproduced with permission from RISE, copyright RISE, 2024)

Combined Analysis. The above outlined methods together with the operational know-how of the consortium partners form the basis for the target energy savings potential of the Orcelle demonstrator vessel. The expected potential energy savings for the given trade scenarios shows that approximately 50% total energy savings is achievable at 14 knots and even increased savings, as the trading speed reduces, compared to the latest generation car-carriers operating with same amount of cargo at 16 knots. Comparing energy savings at the same vessel speed gives a total energy reduction of approximately 40% at 14 knots and 45% at 10 knots only from wing system. A part of the challenge for wind propulsion is to develop operational models and vessels for lower speeds, which is a key to moving to the largest emission reductions using wind.

The Oceanbird Wing Concept. Wing sail technology is not in itself a novel technology; it has been in fact utilized for sailing for a century or more. However, as to its application to commercial shipping, wing sails still have not entered the market to any significant degree. The wing sails solution for Orcelle, called *Oceanbird Wing,* has been developed by the Swedish company Alfawall Oceanbird. It consists of a 40m tall main wing and a flap, which can both be rotated independently to provide optimum thrust forces. The wings are made in composite shells, which provides the aerodynamical shape of the wing sail and transfers pressure loads to the main load-carrying structure. In unfavorable and extreme wind conditions and in port, the wings are folded down (https://www.theoceanbird.com).

Full Scale Demonstrators. The Orcelle project will realize two full scale demonstrator ships, namely one retrofit wind-assisted vessel planned for 2024 and one newbuilt vessel at the project's end (2027). The two demonstration campaigns have several purposes: to provide data for verifying and improving the simulation tools, to improve the next generation of the wing technology, and to prove that the solution is viable in commercial shipping. The retrofit demonstrator installation will be performed on an existing Pure Car and Truck Carrier (PCTC) vessel of the Wallenius Wilhelmsen fleet (*MS Tirranna*, IMO: 9377523). The planned newbuilding will be a PCC carrier with a capacity of 7,000 cars, bound to the Transatlantic route from Europe to the North-East Coast of USA.

A first adaptation of the developed weather routing system will be implemented onboard the demonstrator vessel to enable crew feedback and training as well as develop strategies for optimal onboard usage. The energy savings on retrofit market segment will be proven through dedicated sea trials as well as by analyzing fuel consumption over longer periods of operation. Sea trials consist of tests over a short time period (1–2 days) where the environmental conditions, the ship's speed and power consumption are recorded carefully while the ship is driven alternatively by engine and by sails. The new built vessel Orcelle ship (Fig. 1) will be in commercial operation from day one. The viability will be proven throughout all aspects of ship operation from emissions, safety, crew aspects to logistics and cargo owners' perspective. Such holistic demonstration campaign goes beyond anything publicly known in this area. For the verification of energy efficiency, the Orcelle project will advance the newly developed sea trial procedure further to make it applicable to large ships in fully sailing condition. This will pave the way for open and transparent verification of all future wind ships.

Further Applications. Feasibility studies will be carried out for a range of other ship types than the ro-ro car carrier Orcelle. At least four generic ship concepts (tanker, bulk carrier, containership, ferry) will be developed in close contact with the shipping industry. Design concepts that are based on a logistic and an operational profile, will include the ship's hull form, wind propulsion arrangement, machinery power and propulsion plant, cargo and other main arrangements. The validated simulation tool kit will be used to evaluate the CO_2-saving potential compared to conventional ships and demonstrate viable business models (Plessas-Papanikolaou, 2024).

3 Conclusions

Several cargo ships have already adopted wind assisted power solutions to reduce GHG emissions. However, for deep-sea shipping with large cargo vessels, wind solutions have so far been limited to systems providing yearly energy efficiency reductions of up to (at best) 20%. The Orcelle project aims to develop and demonstrate a cost-efficient approach to reduce emissions and energy use more drastically, namely up to + 50% (estimated for all energy used in operations) and further improve this margin through operational optimization or adjusted service speeds. The emission reduction is herein achieved through the drastically improved energy efficiency, while a part of the onboard energy is taken over by cost free and clean wind power. This means that alternative fuel approaches have the potential to become even more cost-efficient, making the two solutions complimentary (hybrid concept). A significant scientific impact of the project in areas such as multi-fidelity performance prediction methods, wind power control systems based on machine learning, and novel design processes is also foreseen. Finally, an impact on the traditional business scenario modelling by involving the cargo owners (here: Orcelle partner Volvo Cars and other interested European car makers) from the beginning may be expected.

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OPTIWISE Sailing into the Future: Wind Assisted Propulsion of Ships

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Abstract. This paper presents findings of the Horizon Europe project OPTIWISE, which focuses on developing innovative design methods for ships equipped with wind-assisted propulsion. The project encompasses comprehensive evaluations, including environmental, economic, and business impacts. Three distinct design cases are explored: a bulk carrier using Rotor Sails, a tanker fitted with Oceanwings, and a passenger vessel with Solid Sails.

The wind-assisted propulsion systems are detailed, along with the design and evaluation methodologies employed. Rotor Sails harness the renewable power of wind through the Magnus effect, significantly reducing fuel consumption and emissions. Oceanwings provide additional thrust to vessels. Solid Sails, a modern take on traditional sails, are constructed using advanced materials and have versatile applications.

OPTIWISE also introduces innovative design and evaluation methods that consider the holistic impact of wind propulsion on ship design. The need for a more integrated approach is emphasized, where all relevant subsystems are evaluated and optimized together, considering the full operational conditions.

As the shipping industry journeys towards sustainability, wind-assisted propulsion systems offer a promising solution. OPTIWISE's insights and methodologies contribute to the adoption of these innovative technologies, fostering a greener and more efficient future for maritime transport.

Keyword: Wind assisted propulsion; clean shipping; energy management; ship optimisation

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1 Introduction

The shipping sector is transitioning to zero emission operations. Green fuels will contribute significantly to this but need to go hand in hand with energy reduction. Wind assisted propulsion is an effective solution to reduce the needed energy from green fuels and contribute to greening of transport. Horizon Europe project OPTIWISE develops design methods for ships with wind assisted propulsion, including environmental, economic, and business impact evaluations. The methods are applied to three design cases, a bulk carrier with Rotor Sails, a tanker with Oceanwings, and a passenger vessel with solid sails. With this, the OPTIWISE project brings one of the oldest ship propulsion methods back into the modern-day logistics chain.

This paper describes the wind assisted propulsion systems, the design and evaluation methods, and the three design cases that are in development.

2 Description of Wind Assisted Propulsion Solutions

2.1 Rotor Sails

Rotor Sails (also known as Flettner Rotors) are comprised of tall cylinders which, when driven to spin, harness the renewable power of the wind to provide additional thrust to vessels. The phenomenon of lift created when wind blows a spinning body is called the Magnus effect. On one side of the cylinder the flow is accelerated whereas on the other side of the cylinder the flow decelerates, thanks to the Bernoulli principle this also creates an imbalance in pressure on both sides which in turn causes the Rotor Sail to provide thrust.

Rotor Sails have the possibility to be spun in two directions, clockwise and anti-clockwise depending on the wind conditions. As a result, this additional thrust significantly reduces fuel consumption and lowers emissions.

2.2 Oceanwings

The Oceanwings® is a two-elements wing sail propulsion system aiming to provide additional thrust to the ship it is fitted onto by harnessing the energy from the wind and therefore reducing the fuel consumption along with the emissions. The Oceanwing generates lift to provide propulsion thrust to a vessel. AYRO's standard Oceanwing has a span of 33 m and a chord of 11 m, for an approximate projected area of 363 m^2.

The Oceanwings® are automatically managed by an integrated control system that can adjust the angle of attack of the wind sail, adjust the camber, and reduce the area exposed to the wind.

2.3 Solid Sails

The Solid Sail is a wind propulsion system based on the modernization of the classic soft sails. Made up of carbon and glass epoxy composite panels linked by hinges, the Solid Sail has a "semi-solid" behaviour. The panels deform under the wind pressure to optimize the shape of the Solid Sail and increase its aerodynamic performances. At the same time the composite structure, more resistant than the usual fabric of a soft sail, enable the fabrication of very large sails (over 1000m^2) and durable (25 years of estimated lifespan with respect to the 3 years lifespan of a classic soft sail). The system can be inclined to pass under bridges (Figs. 1, 2 and 3).

Fig. 1. Anemoi Rotor Sails (source: authors)

Fig. 2. AYRO's Oceanwings 3.6.3 system (source: authors)

Fig. 3. Full scale prototype of the Solid Sail (source: authors)

3 OPTIWISE Design and Evaluation Methods

Commonly ships are designed for specific conditions considering speeds and loading conditions. Design is too a large extent also "modularised". This characterisation refers to the current practice that subsystems are largely optimised assuming a weak coupling between the respective subsystem and the ship. For instance, it is checked that the ship can carry the cargo and all its subsystems. However, the influence of subsystems, such as a propulsion system, on the overall ship performance is not evaluated for each individual design alternative. Rather, choices are generally made up-front with very little information on the specific design. With wind propulsion the operational space extends with heel, leeway and rudder angle to be considered along with the fitting of such systems onboard.

These challenges call for a more integrated approach where the stronger coupling between relevant subsystems are evaluated and optimised holistically, in an early stage of the design and considering the full operational spectrum. In OPTIWISE we are developing fast processes for an integrated optimisation together with all stakeholders involved from the early design stage onward (OPTIWISE D1.1).

To this end, MARIN is developing the CREATOR workflow that can evaluate all relevant physics for each design variant. It allows for automated hull and ship geometry generation with a quick performance assessment by using pre-trained surrogate models relying on existing MARIN databases and tools. These databases could in principle consist of both experimental and numerical performance data. The evaluation includes aerodynamics, hydrodynamics, (propeller) propulsion and power generation. And, while annual fuel consumption is optimised based on voyage simulations and realistic variable weather data, seakeeping and manoeuvring calculations are directly run also to ensure realistic performance degradation due to seakeeping and that manoeuvring constraints are met.

RISE is also extending pre-existing tools to conduct, an integrated evaluation and design optimisation. In doing so RISE will emphasise stake holder engagement throughout the process. This will make sure that requirements are properly and completely accounted for and that surprises will not occur at the end of the process.

CORE devised methods to do energy management in view of the inevitable variable propeller loading. The energy systems on board ships with substantial wind propulsion will likely include a larger variability of components.

The proposed Energy Management System (EMS) uses voyage simulation data from a route of a vessel to implement a global optimization for the whole route and produce results about energy savings. The results are a set of Key Performance Indicators (KPIs) and statistical diagrams related to the energy performance of each component of the engine room creating a specific overview of the optimal operational performance of each component. Project outputs will be validated through an economic assessment aiming at confirming vessel performance against business-as-usual scenarios and main competitive characteristics of the studied use cases.

4 OPTIWISE Design Cases

Currently concept designs have been completed and the design spaces and basic configurations have been defined for 3 design cases as characterised below.

4.1 Bulk Carrier with Rotor Sails

For this design case, a Newcastlemax type bulk carrier was selected. Rotor Sails are positioned for optimal aerodynamic interaction. As a rule of thumb, they should be at least separated 7 diameters apart from centre to centre. Given the freedom of a newbuild design, cargo hold sizes and number are adjusted so that more Rotor Sails can be positioned with equal distance between them and following the rule of thumb stated above. This would then lead to 5 Rotor Sails on the side and 1 Rotor Sail on the forecastle.

Figure 4 shows 5 Rotor Sails folded in transverse direction on deck to ensure that they are not in the way of cargo operations in port. When Rotor Sails are positioned to one side of the deck with a folding system it allows a maximum height of the sails (slightly less than the beam of the ship). In a large number of loading facilities the sails can stay upright during the entire loading operation. During unloading operations, it is likely that the crane jib would extend further out than the ships beam, in such situations the Rotors can be simply folded.

4.2 Tanker with Oceanwings

A VLCC (Very Large Crude Carrier) has been chosen for the mission and four vessels' concepts have been compared:

Fig. 4. Proposed deck layout for the new-build concept vessel (source: authors, image produced using Adobe Suite and Blender)

- Vessel A is an existing VLCC used as baseline, exemplifying the present state of the art for crude oil intercontinental transport.
- Vessel B is a retrofit of Vessel A with a set of AYRO's Oceanwings.

Vessels C and D are innovative vessel concepts derived from a holistic design. The concepts have been developed considering several aspects of the existing trade for crude oil intercontinental transport, with focus on the GHG emissions and, for vessel D, wind assisted propulsion.

The mission for Vessel A and B (the retrofit vessel option) is based on "business-as usual"-requirements. For the newbuilt options (Vessel C and D) the mission is based on a future system where aspects such as contract agreement including speed (lower) and time window for unloading (longer) can be agreed on.

The detailed design of the wind assisted tanker (Vessel D) will be carried out during a successive phase within the OPTIWISE project, but the matrix of possible main dimensions has been studied for vessels C and D, and the main sizing has been determined during the conceptual work.

With Vessel D being a design aiming at further reducing the GHG emission, AYRO has been developing the concept for a new larger Oceanwing, the Oceanwing 5.8.8 with a projected area of 588 m^2, a span of 42 m and a chord of 14 m. For this wing size, the resulting height from the deck, including the wing ship interface pedestal, is about 48 m (Fig. 5).

Different propulsion arrangements have also been considered to enhance the ability of the system to meet the power flexibility requirements associated with wind assisted ships' propulsion. In addition, a PTO/PTI can be considered for both a conventional two stroke engine and the more novel pair of four stroke engines with gearbox.

A regular rudder can be used for the WASP vessel, but special consideration should be given to the rudder angle required at different wind speeds and directions and, in general, to the vessel manoeuvrability. Most likely larger rudder forces are required, and this can be achieved either with a larger conventional rudder or by installing a rudder

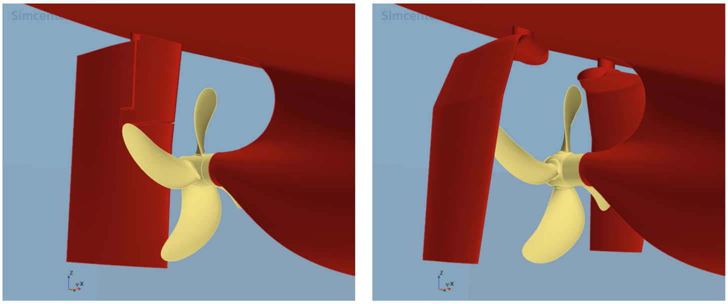

Fig. 5. Conventional FPP and rudder (left), CPP with Gate-Rudder (right) (source: authors)

with flap. A gate rudder can also be an alternative since this type of rudder is less affected by the propeller loading since the blades are not located in the propeller wake.

4.3 Cruise Vessel with Solid Sails

The sailing cruise vessel designed by Chantiers de l'Atlantique is based on the idea that the journey must be as enjoyable as the stay at the destination. The sailing activities shall not impact the activities on board or the comfort of the passengers. Consequently, the heeling due to the wind propulsion system must be evaluated and controlled.

The sails are to be used as a primary source of propulsion, meaning they must be efficient, reliable, with low limitations on the conditions of use. Furthermore, the wind propulsion system must be large enough for the ship to be able to cruise under sails only in favourable wind conditions, without assistance from any fossil fuel. Therefore, the cruising area and the cruising journey are adapted to the speed of the ship under sails, maximizing the up-time of the sails. However, no delay is permitted due to port and passengers' logistic constraints. To meet this requirement, hybrid propulsion (motor and sails) will be used to allow for sufficient range.

This sailing cruise vessel concept designed by Chantiers de l'Atlantique could accommodate 300 persons, for a ship length of about 200 m. The air draft of the ship is limited by the Panama Canal and Suez Canal bridges, a height of 57.9 m. The identified cruising areas are the Mediterranean Sea and the Caribbean Sea.

5 Outlook

OPTIWISE partners are applying the developed design and evaluation approaches to the three design cases discussed in chapter 4. A comparison will be made with conventional vessels to show the energy saving. Furthermore, bridge simulations will be done to involve operators in the developments and to show the use of wind assisted propulsion in operational conditions. Such outputs will be integrated into an economic assessment, aiming at evaluating costs and benefits for deployment of the technologies.

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Lessons Learned from Designing, Constructing and Operating the Methanol-Powered Vessels in the FASTWATER Project

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Abstract. This paper reports on lessons learned during the design of the vessels, including the risk assessments; during the actual build/retrofit; and during the vessels' operation. The focus is on the gained knowledge, to serve as proofs of concept and as a starting point for other methanol vessel conversions.

Keywords: defossilization · waterborne · methanol · emissions · renewable

1 Renewable Methanol as Marine Fuel

Methanol as sustainable energy carrier for defossilizing marine transport is quicky gaining traction. As explained elsewhere [1–4], methanol can be produced at large scale from renewable energy sources and has the unique position of being the most simple hydrogen carrier that is liquid at atmospheric conditions. The latter is a crucial feature for many vessels, for which the integration of gaseous energy carriers such as hydrogen, methane or ammonia would be challenging or impossible. The project's pilot boat and coast guard vessel cases are such examples. A liquid fuel is also the only practical solution for retrofitting many vessels. Compared to other liquid renewable fuels such as biodiesel and HVO (hydrogenated vegetable oil), methanol production is more scalable as it can be produced not only from biomass (bio-methanol), but also from hydrogen produced from renewable electricity (e-methanol) and hybrid routes (e-bio). This scalability explains why methanol is expected to become cheaper than biofuels such as biodiesel in the long term [5]. Its molecular makeup also allows greatly reduced pollutant emissions – with no soot and very low NOx [4].

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The Horizon 2020 project "FASTWATER" [6] set out to advance the experience with methanol as marine fuel, in particular for smaller vessels. The 4 vessels that were or are in the process of being converted are shown in Fig. 1. The vessel specifications and the conversion designs have largely been detailed before, for the tugboat at the previous TRA conference [2], and for the pilot boat in ref. [7]. This paper therefore focuses on the lessons learned while actually converting the vessels, and operating them, in the hope of benefiting upcoming methanol-fueled vessels. The following sections are covering each vessel in turn, apart from the coast guard vessel for which the conversion has just started.

Fig. 1. The 4 demonstrators: a Belgian tugboat (top left - *Reproduced with permission from Port of Antwerp-Bruges, copyright Port of Antwerp-Bruges, 2024*), a Swedish pilot boat (top right - *Reproduced with permission from Swedish Maritime Administration, copyright Swedish Maritime Administration, 2000*), a German river cruise vessel (bottom left – *Source: Authors*) and a Greek coast guard vessel (bottom right - *Reproduced with permission from National Technical University of Athens, copyright National Technical University of Athens, 2022*)

2 Pilot Boat

The pilot boat's design, including the methanol-fueled compression ignition engine and the dedicated bunkering station, was detailed previously [7]. Given that large methanol tankers were already sailing before the FASTWATER project, the conversion of a 14 m boat would seem straightforward. However, applying IMO rules that, for example, stipulate hazardous areas of 6m around a ventilation outlet, to a vessel with only a 4.6 m beam, is obviously impossible. Hence, alternative safety calculations following land-based standards were used instead and it was demonstrated that a safe and efficient design is also possible for a small boat, which is not covered by any specific methanol regulations.

Also, no high speed methanol engines were available as required for powering such a vessel. Hence, a high speed “MD97” methanol engine was specifically developed for this vessel. It was certified for IMO Tier 3 as well as for genset operation. The “MD97” denotes that this is an engine running primarily on methanol (M), but using the diesel cycle (D), i.e. using compression ignition, which is possible when adding an ignition promoter to the methanol fuel. The development work resulted in choosing 3% of ignition enhancer blended in with 97% methanol. Compared to retrofitting an IMO Tier 2 diesel engine to Tier 3, the methanol engine is an easier retrofit as it does not need any aftertreatment whereas a diesel engine would need an SCR system to be integrated, this can balance some of the additional costs for upgrading the tank and safety systems for methanol use.

The high speed engine market gap identified at the outset of FASTWATER was confirmed by the large interest in the MD97 engine, with several engines having been sold and more having been ordered since it was commercially offered. Still, the market is waiting for a high volume OEM to launch such an engine too. Several manufacturers are developing such an engine, targeting 2024–2025 as market introduction date.

The boat was officially launched in December 2021 and has been in regular operation performing piloting duties for the Swedish Maritime Administration since April 2022, clocking up about 350 h so far (with the engine already having run 100 h on test bench prior to being installed in the pilot boat). The performance is on par with a traditional pilot boat and therefore a successful proof of converting an existing diesel pilot boat to methanol. The only problem experienced so far with the pilot boat was during cold weather (down to -15 °C), when the engine became difficult to start and did not respond well to load changes. As mentioned above, the fuel used for the vessel is a mixture containing 97% methanol and 3% ignition improver, to enable the use of methanol (having a high autoignition temperature) in a compression ignition engine. The blend is mixed inline when the vessel is fueled up from the bunkering station, where the methanol and the ignition enhancer are stored separately. The problem was clarified when it turned out that only 1% of ignition improver was in the on-board fuel. The problem was traced back to the bunkering station, where it was found that the ignition enhancer was quite viscous at these low temperatures and the pump simply could not mix enough ignition enhancer into the blend. A simple preheating system for the ignition enhancer tank solved the problem.

3 Tugboat

The safety-focused design of the tugboat, including its fueling system and bunkering procedure; and the work undertaken to develop a medium-speed dual-fuel methanol-diesel engine, was elaborated at the previous TRA conference [2]. During the actual conversion process, several challenges were discovered which are summarized here.

First of all, it is noteworthy to mention the long tendering procedure to assign the conversion works to a contractor. A world-first conversion inevitably means uncertainty, hence contractors were reluctant to submit. From the publication of the tender document to acceptance of the best and final offer took 9 months.

The steel construction work, including torching and welding to construct the methanol tanks, drain tanks and fuel preparation room, took twice as long as anticipated (6 instead of 3 months). Working in confined spaces to retrofit tanks to an existing vessel, during a summer heatwave, were the most important reasons for this.

Several key components took much longer to get delivered (2–3 × longer than originally quoted), or needed additional certificates to be accepted by the governing body. This included the double wall piping system and valves for methanol; the nitrogen generator for the inerting system; and the instrumentation and vessel automation system. The latter is much more complex for a dual fuel engine: over 160 additional signals needed to be ordered, routed, connected and programmed by the integrator.

There were also some knock-on effects caused by some of these delays. For example, the application of the coating needed for the steel tanks to make them methanol-resistant, needs a minimum temperature. As the delays meant that water temperatures had dropped, this required an additional drydocking. Additional climatization measures had to be applied to achieve the required ambient temperature and humidity in the cofferdam, methanol tank, drain tank and fuel preparation room.

The surface preparation took much longer than expected as the complexity of the steel structure did not allow quick work. The coating is subject to a spark test which was not foreseen in the initial lead time. This reflected in a total lead time of 16 weeks.

Besides these delays, some unexpected consequences popped up resulting from choices taken during the conversion process. Two major ones had to do with the fire suppression system and the double-walled methanol piping. The original CO_2 fire suppression system would initially be expanded with 8 additional CO_2 bottles. The existing locker needed to be extended to accommodate these CO_2 bottles. To avoid this, it was decided to replace the CO_2 system with a NOVEC system instead in order to eliminate the extension of the CO_2 storage room, as NOVEC bottles are allowed to be located in the engine room whereas CO_2 bottles are not. Unfortunately, any change in the fire suppression system means one has to comply with the latest ES-TRIN rules, which implies that the air intake of the engines should be adjusted from within the engine room to the deck. Because of the technical complexity of doing this, a motivated request for a derogation has been submitted to the CESNI (the European governing body for inland waterway regulations) working group on technical requirements. At the time of writing, the decision is not known yet.

For the double-walled piping, there is also an unresolved issue currently. The design, approved by classification society and project partner Lloyd’s Register, relies on vacuum monitoring of the annular space of the double-walled piping for leakage. If the inner wall or the outer wall leaks, the pressure will increase and thus the leakage will be detected. However, the vessel’s classification authority requests nitrogen inerting of this annular space. The design preferred to avoid this so that the leakage of oxygen-displacing gas, such as nitrogen, into manned spaces was prevented. This issue is still being discussed.

Another noteworthy point concerns the engine conversion. Current regulations stipulate that in the event of a “major” retrofit, the engine should comply with the latest emission regulations after the retrofit. Previous experience has shown that retrofitting a diesel engine to dual fuel operation with methanol, basically consisting of the addition of the methanol fuel supply system, can result in large reductions in emissions of soot and NOx [8], of the order of 70%. However, if the latest regulations mean a reduction of over 70% is necessary, there is no incentive for such a retrofit: as the dual fuel engine can still operate on diesel, it will need the latest aftertreatment system as well to comply with the emission regulations. After many meetings with CESNI a temporary derogation was granted on the condition of an emission monitoring campaign showing emissions cuts versus the original diesel engine. With a dual fuel engine, due to the presence of an air-fuel mixture, emissions of CO and unburned fuel can be higher than the base diesel engine, therefore it was then decided to integrate an oxidation catalyst to the engine exhaust system, complicating the retrofit process.

4 River Cruise Vessel

The river cruise vessel is the only demonstrator in FASTWATER that will not be built, but instead will be delivered as a thorough feasibility investigation of converting a specified diesel-powered river cruise vessel to a methanol-powered one.

The basis for the conversion investigation is the “Viking Longship class”, which is a commercially mature series with more than 50 ships of this class having been built since 2012. With a typical range of 14 days, the first task of the investigation was to study methanol storage options, aiming for an operation with an acceptable autonomy while keeping the impact on the number of (money-making) passenger cabins limited. Initially, the availability of engines running nearly 100% on methanol was assumed. This implies a costly replacement of all engines, but the maximum achievable emissions reduction. The major challenge for implementing such a concept is the lower volumetric density of methanol compared to diesel, a factor of 2.5 × lower. The incorporation of a high enough amount of methanol in the existing ship design was solved with only a minor impact on the number of cabins. However, after repeated evaluations of the engine conversion possibilities with engine manufacturers, it was found that the only engine available on the market to achieve such a high methanol energy fraction (MEF) is the MD97 engine developed within FASTWATER, but its power range cannot meet the power requirements of the river cruise vessel. Hence, a second methanol storage concept was elaborated which takes into account the limited MEF achievable with the commercially available dual-fuel engines.

With a slightly reduced autonomy requirement (to 10 days), assuming a maximum of 70% MEF during mid-load operation, and running on diesel-only mode during low and high load operation, the required volume of the methanol storage could be greatly reduced and all cabins could be retained. Based on this new storage concept, the design of the methanol fuel system including bunkering, piping, and venting, as well as the stability analysis of the vessel has been concluded. The investigation is currently focusing on the safety system, where the sensors, equipment and their functional behaviors will be further treated in the subsequent HAZID risk assessment.

The principal design considerations and findings were provided to the CESNI committee for the development of rules for inland waterway. In particular, this helped to develop the ES-TRIN (European Standard laying down Technical Requirements for Inland Navigation vessels) regulation’s chapter on methanol storage and the chapter for the usage of methanol as fuel in combustion engines.

5 Conclusions

This paper reported on lessons learned while designing and executing the retrofits of vessels to methanol operation. This included increased knowledge in handling methanol, particularly as MD97 blend; how existing rules do not consider retrofitting in a practical way and therewith contribute to its prevention; and the need to adapt the CESNI rules. It confirmed the demand for a wider range of methanol engines on the market (currently being addressed) and most importantly: that ultimately, running a vessel on methanol is feasible with little extra effort.

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A Path toward a New Generation of Green Hybrid Powertrain: The PHOENICE Project

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Abstract. Nowadays the synergic use of powertrain electrification and innovative Internal Combustion Engine (ICE) technologies may represent a valuable solution to face the concurrent tightening of pollutant emission limits and CO2 targets and to shift toward a more sustainable mobility. In this context, hybrid powertrains are seen as the main near-term solution to these challenges of reducing CO2 and pollutant emissions as well as meeting the demands of the global market in the near future. In such a framework the PHOENICE project aims at assessing the capabilities of a plug-in hybrid powertrain to minimize the fuel consumption of C class SUV in real world driving conditions and at the same times being compliant with the upcoming EU7 regulations.

For the achievement of these ambitious targets, the development of an environmentally friendly internal combustion engine is mandatory. Thus, this paper will focus on the design of the PHOENICE engine which combines innovative in-cylinder charge motion (Swumble™), lean mixture with cooled EGR, and electrified turbocharger to enable a highly diluted, efficient combustion process. The abovementioned engine concept was also coupled with a dedicated aftertreatment configuration composed by an electrically heated TWC, a GPF and an SCR optimised for gasoline exhaust conditions whose high conversion efficiency allows the minimization of the tail pipe emissions.

The optimization of such a complex configuration relied on an extensive use of numerical models which allowed reducing the calibration effort and identifying all the possible synergies among the selected technologies. The results of this extensive simulation campaign showed a very good agreement with the preliminary experimental measurements carried out on the first prototype of the engine which achieved an increase in Brake Thermal Efficiency (BTE) of more than 4 points compared to the reference layout.

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Keywords: hybrid powertrain · Internal Combustion Engine · CO2 · Low Carbon · Pollutant emissions

1 Introduction

The European Council have recently adopted a regulation setting stricter CO2 emission performance standards for new cars and van in the frame of 'Fit for 55' package [1]. The new rules aim to reduce tank-to-wheel CO2 emissions of passenger cars by at least 55% by 2030 compared to 1990 levels. The challenge will also be to reduce air pollutant emissions, as through the upcoming Euro7 legislation [2], for example, to improve air quality and decrease noise, both of which impact citizen health. Considering powertrains, there is not a unique and ideal option that solves all the demands of sustainable mobility while addressing local and global environmental impacts, energy diversification goals, and the requirements of global markets and European competitiveness. This objective can only be achieved through a massive shift from fossil energy carriers to renewable electricity or hydrogen, along with the use of new alternative and renewable fuels matched with advanced internal combustion engines and highly electrified powertrains. In this context, hybrid electric powertrains are viewed as an interesting mid-term solution to reduce fuel consumption and exhaust pollutant emissions of light-duty vehicles (LDVs) while also meeting the evolving market demands. The present paper describes the PHOENICE (PHev towards zerO EmissioNs & ultimate ICE efficiency) project, which is an EU H2020 project [3]. The primary objective of this project is to showcase the full potential of a plug-in hybrid vehicle, specifically optimized to significantly reduce fuel consumption and pollutant emissions in real-world driving scenarios. To achieve this goal, the project aims at reaching a Technology Readiness Level (TRL) 7 system, combining:

- A dual dilution combustion engine designed to achieve 47% peak efficiency
- An innovative exhaust after-treatment system
- A waste heat recovery (WHR) system to enhance the overall efficiency
- An advanced Vehicle integration and control according to an emissions-based Energy Management Strategy (EMS).

The PHOENICE concept will also comply with the upcoming Euro 7 regulations and meet the emission levels outlined in the European Commission's Horizon Prize for the Cleanest Engine of the Future.

2 The PHOENICE Engine Concept

The internal combustion engine is a key component of the PHEV demonstrator vehicle. Based on the overall performance requirements of the PHOENICE project, the main features of this gasoline diluted engine are selected and optimised based on 0D simulations and 3D CFD calculations [4]. The baseline engine is a GSE T4 Stellantis 4-cylinder in-line turbocharged spark ignition engine with a displacement of 1.3 L [5]. In the initial phase, optimization was conducted using 3D CFD (Computational Fluid Dynamics) to enhance the charge motion and optimize related intake ports, compression ratio, and piston shape. The objective was to implement Swumble™-like complex in-cylinder charge motion [6] and develop an optimized dual dilution combustion system. This system incorporates both lean (Air) [7] and EGR dilution [8], along with early or late intake valve closing, with the aim of mitigating knock and achieving higher thermodynamic efficiencies. This specific type of charge motion is designed to generate enhanced turbulence while minimizing the impact on the flow capacity of the intake ports.

2.1 SWUMBLE™ In-Cylinder Motion

The IFPEN Swumble™ concept is an innovative approach aimed at enhancing in-cylinder turbulence to improve engine efficiency across various operating conditions. It is particularly well-suited for early and late intake valve closing strategies, high dilution rates, and high compression ratios, resulting in improved combustion speed and higher thermodynamic efficiency. To ensure the optimal application of the Swumble™ concept to the baseline cylinder geometry, a 3D-CFD flow simulation test bench was utilized. This test bench allowed for the assessment of the impact of various geometrical modifications on the internal fluid dynamics. Within the design optimization loops, two intake valve lift profiles—Early and Late intake valve closing—were taken into consideration for each geometrical modification. The results of the optimization process indicate an increase in turbulence by approximately 50% [4], through the implementation of Swumble™ as shown in Fig. 1.

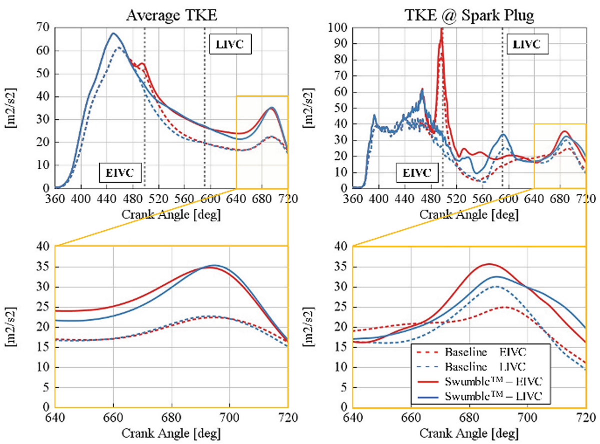


Fig. 1. Left: average TKE in the cylinder – Right: TKE at the spark plug, averaged on a 5 mm box. EIVC and LIVC configurations

2.2 Engine Concept: Selected Technologies

2.2.1 Design/Manufacturing of the Prototype Cylinder Head and EGR Loop

Once the main features of the combustion system and technological bricks were selected (Fig. 2), the new cylinder head, the new air path and the Low-Pressure Exhaust Gas Recirculation (LP EGR) loop were designed and validated by finite element analysis and computational fluid dynamics simulations.

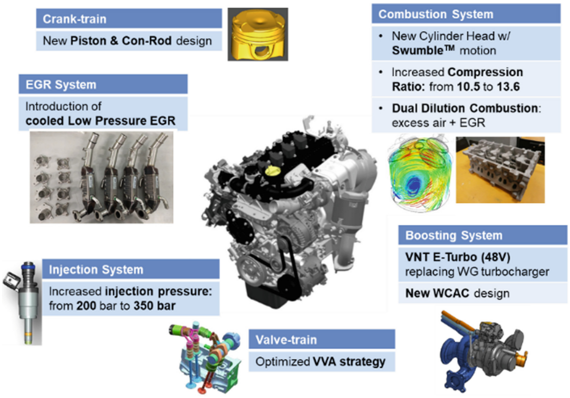


Fig. 2. Features and Modifications of the PHOENICE Engine Compared to the Baseline [5]

4 cylinder heads were manufactured, and their quality was ensured through rigorous inspection using the Tomography technique. Furthermore, prototype connecting rods, capable of handling higher in-cylinder pressure, were integrated into the engine assembly. The piston heads were machined according to the optimized shape obtained through the 3 CFD optimization process. Subsequently, the newly designed injection system, along with the EGR (Exhaust Gas Recirculation) loop and updated Air-path, were assembled onto the prototype engines.

2.2.2 E-Turbo

The design of the EGR and air loop integrated a new E-Turbo, which was specifically developed for the PHOENICE project. This E-Turbo features:

- High temperature resistance Variable Nozzle Turbine (VNT) replacing the Waste-Gate (WG) turbine of the baseline engine.
- Ball Bearing technology to allow synergies with the exhaust after treatment.
- High speed electric machine integrated in the turbo's shaft and 48V Inverter.

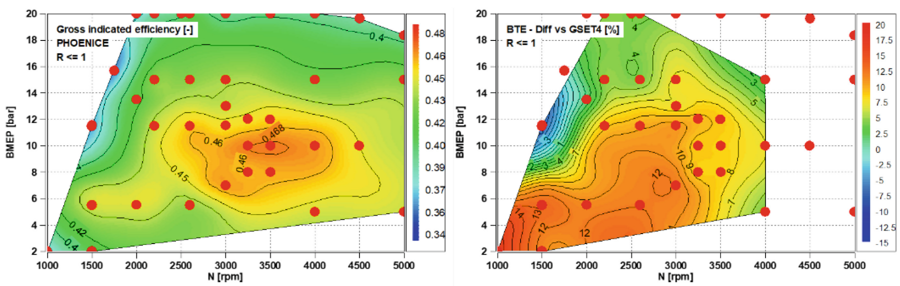
Turbomatching for the new PHOENICE lean combustion system was performed by means of the virtual test rig developed at Politecnico di Torino [4] through the commercially available 1D-CFD code GT-Suite [9].

2.3 Numerical Model Validation and Preliminary Numerical Optimization

The digital twin of the PHOENICE engine was developed in the commercially available software GT-Suite, a 1D-CFD code developed by Gamma Technologies. This virtual test rig features a predictive combustion model [10]. The tuning parameters of the model were calibrated using a preliminary set of experimental points collected on an initial PHOENICE engine prototype that retained the baseline engine turbocharger and exhaust line. The validation of this model demonstrated satisfactory agreement, with a maximum error of just over 5% when comparing numerical and experimental values. After the validation described above, the developed 1D-CFD engine model was employed as a virtual test rig to conduct preliminary calibration for the complete engine.

2.4 Steady-State Calibration

The PHOENICE Dual Diluted Combustion Approach engine has been installed and validated in a multi-cylinder engine dynamometer test bench. The initial task involved validating the functionalities and stable control of all sub-components on the test bench under steady-state conditions and performing a pre-calibration using the developed virtual test rig. Once the control calibration for actuators was completed, an engine calibration phase was performed in steady-state conditions by controlling and optimizing all the available actuators (e.g., spark advance, injection parameters, dilution rate, VNT position and VVA angles for opening and closing events of the intake valves).



(a) (b)

Fig. 3. (a): Gross indicated efficiency map after optimization. (b): Brake Thermal Efficiency (BTE) improvement of PHOENICE engine versus the reference engine. Images produced using CONCERTO software.

A specific sequential methodology of optimization has been set to achieve the lowest fuel consumption while minimizing the pollutant emissions. This calibration has been performed on 37 operating points: 23 operating points defined through 0D simulation and representative of the real engine operations, 6 specific operating points to assess the maximum efficiency potential and 8 points in full load conditions. Figure 3.a shows the gross indicated efficiency maps after optimization. The red circles indicate the operating points that were realized. A maximum gross indicated efficiency of 47% is reached for 3250 rpm x 10b BMEP and 3500 rpm x 10b BMEP. The BTE (Brake Thermal Efficiency) improvement from the reference engine to the PHOENICE engine is also illustrated in Fig. 3.b, showing a gain of 5 – 15% thanks to the modifications made to the base engine.

3 Conclusions

An innovative lean-burn spark ignition engine concept was developed, based on a state-of-the-art Stellantis 1.3-L gasoline engine. A novel electric turbocharger was specifically designed for the PHOENICE project. To aid the calibration of the PHOENICE engine, a fully virtual test rig was developed. Encouragingly, the engine prototype testing demonstrated remarkable results, achieving a gross efficiency of 47% and substantial improvements of around 10% across a wide operating range. The first vehicle simulation, considering these experimental results, showed an approximate 8% improvement in fuel consumption compared to the baseline. For the future, optimization efforts will continue under transient operating conditions. By 2024, a vehicle demonstrator will be ready, providing the final assessment of the project's objectives.

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Latest Reliable Power Electronics Technologies for Zero-Emission

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Abstract. This paper presents use cases to demonstrate the advances in simulation, prognostic health management and digital twins, and power electronics for electric vehicles and gives an insight into the potential for the end users in the future.

Keywords: Electromobility · Design and Optimization · Reliability · Wide-bandgap Semiconductors · Digital Twin

1 Introduction

At the end of 2019, the European Commission presented "The European Green Deal". The most important objectives thereby are the reduction to zero net greenhouse gases emissions by 2050 and to ensure economic growth decoupled from resource use. HiEFFICIENT project – a Research and Innovation Action funded by the KDT Joint Undertaking – directly addresses these objectives targeted, having a focus on sustainable mobility and resource efficiency. By making use of highly reliable and integrated wide-bandgap (WBG) technologies in electronic power systems of electrified vehicles, testing systems, and charging infrastructures, HiEFFICIENT directly supports the development towards a more resource-efficient and decarbonized transportation system.

Today, the applicability of WBG semiconductors in electrified vehicles has been demonstrated, but only Silicon Carbide (SiC) is assumed by manufacturers to be introduced in vehicles in the next 3 years, but so far not Gallium Nitride (GaN). Therefore, the project has set a focus on the implementation of GaN devices in automotive applications. Furthermore, reliability becomes an issue to achieve sustainable eDrives and hence the project thoroughly investigates methodologies and strategies to enhance the lifetime and reliability of tomorrow's vehicle power electronics utilizing real-time prognostics and health monitoring (PHM). Nowadays, the advancement of sensorics and Industrial

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Internet of Things (IIoT) devices and network technologies enables intelligent edge monitoring to estimate remaining useful lifetime (RUL) in real-time and data-streaming to the cloud. The cloud leverages data from multiple EVs, forms big data analytics and machine-learning-based models, and takes necessary steps to enhance lifetime.

Therefore, the paper is prepared in three sections, highlighting advances in the project exemplarily, (1) GaN technologies for automotive PE applications, (2) Thermal simulation for power electronics applications, and (3) Power electronics design for reliability.

2 GaN Technologies for Automotive PE Applications

With the main technical drivers of OEMs being efficiency improvements, cost reductions and increase of power density, as well as the need to increase sustainability parameters, all new technologies are investigated to see how well they do support these objectives. GaN is next to SiC another, in many aspects similar, wide bandgap material of interest because it promises cost advantages. How good this can be utilized and what additional technical opportunities it enables differ for the various PE applications: OBC and DCDC, high power traction inverter, *low power auxiliar inverters* and with the battery voltage levels: 48 V, 400 V, 800 V to 1000 V.

In 48 V to 400 V systems' OBC and DCDC one GaN switch could replace one SiC switch and the high switching frequency is used to decrease size and weight of external components like magnetics making it a lower cost solution than SiC with higher power density than IGBTs. With no 1200 V GaN devices available today and in the near future a multilevel topology is necessary in 800 V to 1000 V Vbat powertrains. For DCDC several projects have already shown that there are promising advantages of multilevel with regards to EMC and further magnetics reduction that can compensate the higher effort of two or more switches vs. one SiC switch. The challenges with GaN are the versatile suppliers' solutions that make drop-in second source choices difficult for OEMs to secure their supply chain.

For traction inverters the situation is more challenging. Research needs to continue to develop reliable solutions for high powerstage solutions > 150 Arms. However, for 48 V to 400 V Systems lower cost and improved drive unit efficiency at slightly higher switching frequencies of, e.g., 50 kHz compared to SiC are highly promising to address two of the main drivers of OEMs.

In HiEFFICIENT project a solution for a high power GaN powerstage with phase-currents up to 500 Arms is developed. It utilizes GaN half-bridges that are assembled in parallel to achieve various levels of output current. The modularity supports overall platform cost reduction and the newly developed embedded powerstage enables highly compact designs. With the improved thermal dissipation, a higher lifetime for a given number of dies will be targeted, further reducing cost, and improving sustainability.

Multilevel topologies for 800 V promise system advantages by reduced harmonic distortions for EMC and thermal aspects that also involve the eMotor and battery. Today a higher switching frequency than 20 kHz - 30 kHz is not necessary but might become more important with new eMotor developments and more advances in pulse pattern research to improve NVH and efficiency by software measures.

3 Thermal Simulation for PE Applications

Thermal modeling plays an important role in the development of power electronic systems and is key to understand the causes of correct or incorrect thermal behavior; it builds the basis to understand the health of the system and predict the lifetime. Since liquid cooling is increasingly applied in power electronics, 3D studies are essential because local flow characteristics on the coolant side have a significant impact on cooling effectiveness and temperature hot spots.

Traditional thermal modeling approaches [1], such as Cauer, Foster, Lumped parameter models, etc. represent the state-of-the-art in heat transfer simulation in power semiconductor modeling. However, to investigate the cooling performance in a more detailed way, an extended 3D CFD simulation methodology is needed. Modern power electronic modules exhibit multiple material layers. Hence, the applied simulation software requires multi-material and multi-physics capabilities, which is provided by the commercial software package [2] AVL FIRE™ M.

The considered cooler geometry is taken from a demonstrator of a 650 V GaN based power converter, based on a multiphase phase evaporation cooling approach. A special challenge in this task lies in the channel dimensions dealing on the micro scale level, as channel widths of 100 µm are used. The simulation domain is displayed in Fig. 1 showing one segment with four GaN chips on top of the multi-layer solid structure. The four chips provide a heat input of 4 x 20 W into the segment. A methanol/water mixture with a flow rate of 45 ml/min is entering the domain with a temperature of 35 °C. The simulation mesh consists of 1.8 million, mainly polyhedral, elements with a proper boundary layer structure in the fluid region to fulfil requirements for correct heat transfer calculation. The applied RPI (Rensselaer Polytechnic Institute) wall boiling model is an advanced approach to deal with the nucleate boiling regime [3]. Seen as a major target in this simulation the average temperature at the interface between the chips and the interposer material is kept at approx. 83 °C which is within specified limits. As a qualitative measure the distribution of the built-up of the vapor volume fraction of the coolant is also checked. Together with other quantities, e.g., flow field parameters, it provides ideas to improve the flow path and thus the heat transfer.

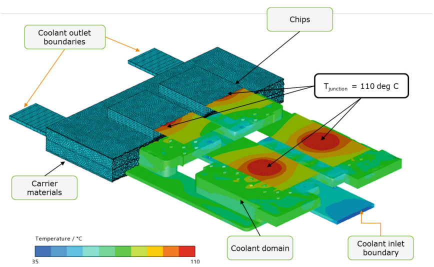

Fig. 1. Considered segment of a GaN 650 V demonstrator simulated with AVL FIRE™ M

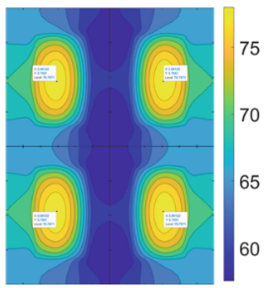

Fig. 2. Temperature at chip interface obtained by analytical model with Matlab2023a.

The applied simulation approach provides the proper tools to start investigations in an early stage of the design, because local flow characteristics on the coolant side have a significant impact on cooling. Furthermore, the results are in line with the analytical microfluidic flow boiling model, which is used to design the cooler geometry, see Fig. 2. Issues, which are detected early in advance, can avoid expensive cycles of iteration during prototyping and manufacturing phase. Furthermore, the application of RPI model includes most of the thermal management systems (e.g., general cooling phenomena in power electronics, water cooling jacket, battery cooling) in which evaporation phenomena are used to absorb heat and carry it out of the system.

4 Power Electronics Design for Reliability

With the recent advancement of Wide Band Gap (WBG) semiconductor technologies, SiC and GaN-based converters have taken the forefront [4]. The WBG semiconductors allow much higher switching frequencies and temperatures than conventional semiconductor materials. WBG-based converters have the potential to operate at elevated junction temperatures exceeding 150 °C, owing to their high thermal conductivity. Moreover, WBG converters operate at faster switching. Filtering components contain passive components (e.g., dc-link capacitors, magnets), which are relatively large and heavy. Higher switching frequencies make it possible to use smaller filtering components, which in turn allow a lighter and more compact system. At the same time, the higher switching rates result potentially give more switching losses, which eventually lead to higher temperatures. And according to the reliability study in articles [5, 6], the lifetime of the power electronics converters reached their limits by the progressive fatigue of the semiconductors due to repetitive subjected thermo-mechanical stress.

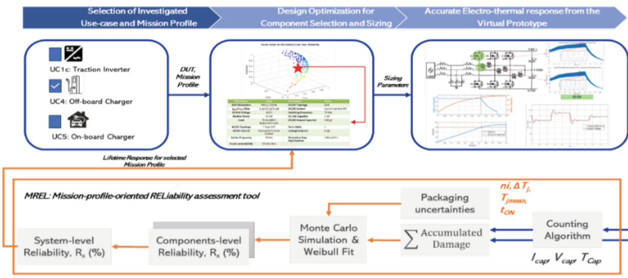

Fig. 3. A streamlined framework for reliability-oriented design and optimization for different HiEFFICIENT UCs (i.e., traction inverter, off-board charger and GaN on-board charger).

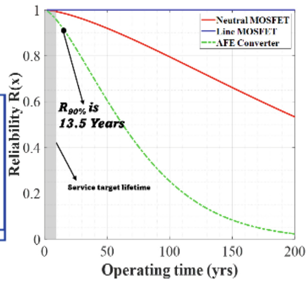

Fig. 4. Weibull reliability of the charging system for the considered charging current profiles.

Therefore, a streamlined approach is required to balance optimal component sizing, select appropriate switching frequencies to minimize losses and fulfill service lifetime requirements, which could reduce over-engineered hardware significantly. In this paper, a streamlined process to design and optimization for reliability (*DOfR*) is proposed (cf. Fig. 3), which will be used to investigate the reliability of the optimal automotive powertrain components based on mission profiles, according to the following steps: i) once the optimization of the components is completed this tool will estimate the lifetime of the new components for the targeted mission profile based on the repetitive electro-thermal stressors; ii) if the new components' target lifetime is not reached, the tool will provide input to the optimizer to re-optimize based on the reliability scorecard. Thus, this tool will allow automotive power electronics engineers to (a) optimally size components without compromising reliability and avoid over-engineered hardware and (b) decrease the environmental footprint during operation and prolong the component's lifetime to fulfill the service target.

Within HiEFFICIENT project, a multi-use DC charger that can be seamlessly used for small vehicles (48 V battery voltage), personal cars (200–920 V battery voltage), and heavy-duty vehicles (500 V-1000 V battery voltage) is being developed. The maximum power of the charger is 180 kW; hence, 3 modules of 60 kW and 3 outputs will be available. The connection of each module to one of the outputs is handled by controlling the power-switching matrix. The module of 60 kW is also composed of two equal 30 kW building blocks (BB). For the 30 kW BB module, a two-power conversion stage architecture is chosen. For the AC/DC stage, T-Type Active Front End (AFE) is selected since it has a smaller LCL filter compared to a standard 2-level AFE. For the DC/DC stage, an isolated DAB (Dual Active Bridge) topology is selected. In this paper, only the 30 kW T-type AFE converter is considered as the device under test (DuT). A multi-objective genetic algorithm-based (MOGA) optimization for the 30 kW AFE converter is developed to obtain performance improvement regarding converter-level cost, size and lifetime. Considering the obtained optimal solution, a virtual prototype of the converter is prepared using commercial PLECS software to simulate responses for the entire grid-to-vehicle (G2V) and vehicle-to-grid (V2G) events. A Look-up-Table (LuT) based detailed switching and conduction losses are estimated along with a foster thermal network, where the ambient temperature is retained at 250 ˚C. Based on the repetitive junction temperature (Tj) and junction temperature swings (ΔTj) response, the cloud-based reliability assessment framework described in the article [5] determines the actual lifetime of the converter at the subjected mission profile.

Figure 4 illustrates the AFE converter reliability as a function of the operating time in years, as the aim of this paper is to assess the impact of mission profile (i.e., G2V and V2G charging) on the lifetime of a high-power charging system, it is assumed that the DuT will be subjected to 10 same profiles/day during its entire life cycle, which means daily the charger will operate for 370 min and each time ambient will be remaining same at 25 ˚C facilitated by pre-conditioning before each mission profile cycle. Besides, it can be seen that for the 90% reliability percentile, the DuT exhibits a lifetime of 13.5 years, satisfying the OEM's requirement of 10 years. However, it must be noted that the actual lifetime of the DuT will likely be shorter than the predicted values shown in Fig. 4 as there are other failure-prone components (e.g., DC-link capacitor, LCL filter elements, micro-controller, etc.), which have not yet been factored into this framework.

5 Conclusions

The paper presented several aspects of developments in HiEFFICIENT project. GaN technology is a key enabler for future power electronic automotive applications. Due to some today's limitations innovative approaches are necessary to fulfil all market needs.

Sustainability and long lifetime are in focus of OEMs and hence advanced cooling technologies and development tools are key as well as frameworks for lifetime estimation and appropriate design. All these aspects are addressed in the one or other way in HiEFFICIENT project, tackling the needs of future applications.

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Development and Analysis of Rightsized Powertrains for Small Urban Vehicles

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Abstract. This work provides an overview of the key steps involved in designing an electric powertrain for an L7 category vehicle intended for urban and suburban environments. It focuses on mission-specific rightsizing and physical integration into small vehicles. Synthetic driving cycles of Helsinki, Finland, and Regensburg, Germany, created via activity-based transport modeling and dynamic vehicle simulation reveal that urban use cases do not require high power and torque. This allows for smaller battery capacities and electric motor ratings, leading to cost savings in mass production. Moreover, this paper introduces two powertrain variants: a low voltage option and an extensive high voltage option with both conventional conductive and wireless charging systems. The high voltage variant was selected for implementation and for that, the first measurement results are presented. Both low voltage and higher voltage options are technically feasible, but if wireless charging is preferred, the higher voltage configuration is more suitable from a system design perspective.

Keywords: L7 category vehicle · electric powertrain · design · computational analysis · laboratory measurements

1 Introduction

The global share of the urban population is projected to rise to 60% by 2030 [1]. This creates a significant demand for the development and improvement of urban transportation. While walking, cycling, and public transportation are often preferred, for well-justified reasons, they may not be sufficient for all use cases. Then, it becomes essential to innovate other safe, flexible, usable, and emission-free transport solutions.

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The H2020 project Reconfigurable light electric vehicle, REFLECTIVE[1] [2], aims at developing, manufacturing, and testing a completely new L7 category electric vehicle (EV) for urban needs. In this paper, we discuss the main steps of the powertrain designing. Particular attention is paid to the typical missions and rightsizing for those. We present two powertrains: a more affordable low voltage option and a more extensive high voltage option with two different on-board chargers, conventional conductive and wireless. Finally, we discuss the advantages and disadvantages of both powertrains.

2 Rightsizing of an Electric Powertrain

The basic specifications of an EV powertrain can be derived from its intended use cases and missions, and compressed into driving cycle data, to ensure appropriate component sizing. We applied this approach in [3] to establish the powertrain specifications of the REFLECTIVE L7 category EV, designed for passenger and goods transport, with a maximum vehicle speed of 90 km/h. The driving cycles used were defined via combined activity-based transport and vehicle simulation, assessing different urban driving scenarios. The vehicle's longitudinal dynamics were simulated accounting for the resistive forces from slope, rolling resistance, and aerodynamic drag.

The obtained specifications include a nominal power of 15 kW, nominal torque of 40 Nm, and base speed of up to 4680 rpm, which can be achieved at different voltage levels. However, the chosen voltage level has an impact on various aspects of the powertrain, including component size, weight, and costs. In the next two subsections, we present the powertrain design at two different voltage levels (96 VDC as a low voltage and 355 VDC as a high voltage) to assess the voltage's effect on the design.

2.1 Design of Low Voltage Powertrain

A 48 VDC system was initially studied. However, it was discovered that the selected motor type would have operated at excessively high currents if the required torque and power overloadability were to be achieved with this voltage level. Hence, the voltage was increased to 96 VDC. Three air-cooled induction motor designs were then developed and analyzed using the 2D finite element method based on factors such as base speed, nominal power, and efficiency. Table 1 presents the key parameters. The geometry of Motor 1 is shown in Fig. 1(a). The other two designs share the same outer and inner main dimensions as Motor 1 but with varying numbers of pole pairs and stator and rotor slots. Figure 1(b)-(d) present the winding layouts of the motors. An exhaustive analysis was conducted to determine the optimal number of rotor bars for minimizing the torque pulsation at the nominal operating point [4]. The final, most favorable combinations of the stator slots and non-skewed rotor bars are given in Table 1 as well.

Figure 2 presents the calculated efficiency map for Motors 1–3, along with their nominal torque-speed profiles (indicated by red curves). These maps show the motors' maximum achievable torque values without electric current limitations. Among these

[1] Funded by the European Union under Grant Agreement 101006747.

designs, Motor 1 with 30 rotor bars was chosen for its higher maximum speed and better flux weakening capability. This choice aligns with cost-effectiveness as Motor 1 can be produced using conventional methods and readily available electrical laminations.

Table 1. Specifications of the low voltage traction induction motor designs.

Parameter	Motor 1	Motor 2	Motor 3
Number of pole pairs	2	3	2
Number of stator slots / rotor bars	36 / 30	36 / 40	30 / 42
Base speed (rpm)	4680	3500	3000
Number of turns per coil	3	3	4
Stator phase resistance (mΩ, 100 °C)	19.2	17.3	28.4
Torque ripple at nominal point (Nm)	2.6	0.8	2.9
Stator core outer / inner diameter (mm)	200 / 112	200 / 112	200 / 112
Air gap width (mm)	0.3	0.3	0.3
Length of the motor (mm)	160	160	160
Stator voltage L-L rms value (V)	66	66	66

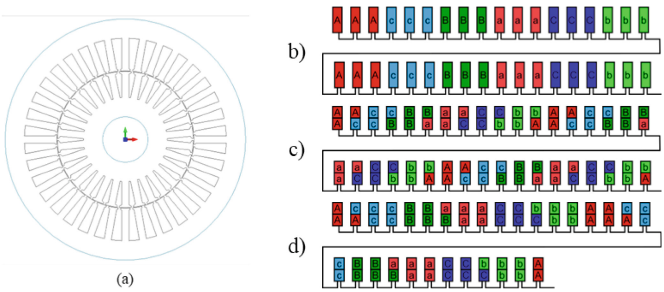

Fig. 1. (a) Cross-section of Motor 1. Winding layouts (b) Motor 1, (c) Motor 2, and (d) Motor 3.

The low voltage motor controller was selected off-the-shelf. Of the present offering, BorgWarner's Gen 4 Size 4 AC motor controller [5] fits our purpose the best. This controller has a maximum output voltage of 80 V, and it is highly configurable for various applications.

Given the maximum vehicle speed and wheel diameter (i.e., 90 km/h and 0.622 m, respectively), the expected maximum wheel rotational speed is 770 rpm. A Benevelli gearbox with several possible ratios and a maximum input speed of 7200 rpm was chosen to achieve the needed vehicle torque [6].

For low voltage powertrains, there are many commercial Mode 2 conductive charger alternatives. Wireless charging, however, is not an optimal solution for such cases. Low voltage wireless chargers are only available as custom-made and hence they are expensive. Also, as the wireless charger's voltage decreases, the charging time, losses, and current for delivering a specific power all increase.

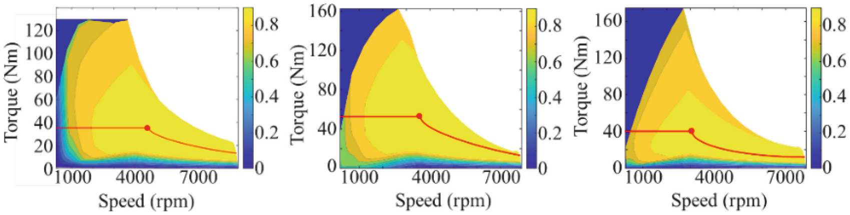

Fig. 2. Nominal torque-speed curve (red line) and efficiency map of Motor 1 (left), Motor (middle), and Motor 3 (right). Source: Authors.

2.2 Design of High Voltage Powertrain

For the high voltage design, we chose a liquid cooling system over air cooling to reduce the motor size and enhance its overload capability. We adjusted the geometry of Motor 1 with 30 rotor bars according to the high voltage and liquid cooling requirements.

Cost-effective scalability is reached by keeping the stator and rotor laminations' geometry and adjusting the motor's length and the number of turns of the stator winding based on the voltage and power needs. Table 2 lists the specifications for three high voltage traction motor designs with identical cross-section geometry but varying stack lengths. The winding for these cases was a double layer fractional slot winding with $q = 3$ and a coil span of 8 slots, having a winding factor of 0.945. Figure 3 displays the simulated efficiency maps of the motors. According to this figure, Motor 4, with a 4000-rpm base speed, exhibits wider high-efficiency regions compared to Motors 5 and 6.

Table 2. Specifications of the high voltage traction induction motor designs.

Parameter	Motor 4	Motor 5	Motor 6
Number of pole pairs	2	2	2
Number of stator slots / rotor bars	36 / 30	36 / 30	36 / 30
Base speed (rpm)	4000	4380	4680
Number of turns per coil	5	6	8
Stator phase resistance (mΩ, 100 °C)	54.0	67.2	101.1
Torque ripple at nominal point (Nm)	1.6	1.6	1.6
Stator core outer / inner diameter (mm)	170 / 96.8	170 / 96.8	170 / 96.8
Air gap width (mm)	0.4	0.4	0.4
Length of the motor (mm)	200	150	100
Stator voltage L-L rms value (V)	225	225	225

The selected off-the-shelf frequency inverter [7] imposed a 400 V voltage constraint. To match the DC voltage levels of the inverter and battery, we utilized 96 Li-ion NMC battery cells connected in series from KOKAM (model: SLPB100216216H [8]). Each of these cells possesses a capacity of 40 Ah, and with a nominal cell voltage of 3.7 V, the battery capacity becomes 14 kWh. This proposed battery configuration ensures that there is sufficient energy to fulfill the anticipated range of the vehicle. The type and number of the selected battery cells result in a nominal battery voltage of 355 V. Considering space vector modulation, the stator line-to-line voltage becomes 225 V (rms).

Similarly, as in the case of the low voltage variant, a gearbox with an integrated differential was selected from the options available at the market. The gearbox has the following specifications: a gear ratio of 1:12.64, a maximum input speed of 10000 rpm, a maximum output torque of 1600 Nm, and 95% efficiency.

A high voltage level allows us to equip the vehicle with a wireless charging solution in addition to the conductive one. In [3], we performed a detailed analysis of the vehicle utilization and based on that specified the power of the charging system as 7 kW.

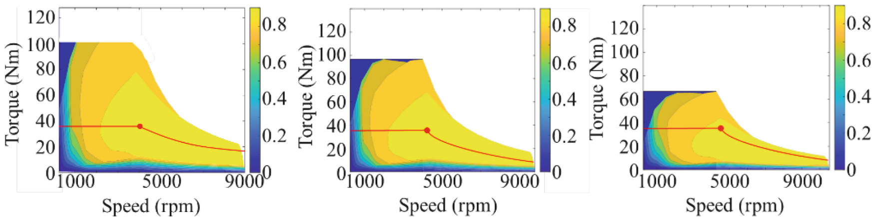

Fig. 3. Nominal torque-speed curve (red line) and efficiency map of Motor 4 (left), Motor 5 (middle), and Motor 6 (right). Source: Authors.

Fig. 4. Powertrain's performance at different driving conditions; a) motor rotational speeds, b) and c) motor target and measured shaft torques, d) battery current, and e) battery SOC.

3 Measurement Results

As REFLECTIVE project includes demonstrations of wireless charging, we have opted for the high voltage powertrain and Motor 4 conducting test bench measurements exclusively for this configuration. The equivalent circuit parameters of the motor were defined first based on a no-load test and a short circuit test with a locked rotor to control the motor precisely. These parameters include the stator and rotor resistances, each with a value of 62.0 mΩ, magnetizing inductance of 15.6 mH, stator leakage inductance of 201.2 μH, and rotor leakage inductance of 128.7 μH.To assess the powertrain's performance, various tests were conducted by varying motor shaft torques at specific speeds, with the concurrent recording of battery current and battery state of charge (SOC). Figure 4 presents the results from these test bench experiments. The entire test took approximately 16 min, during which the SOC decreased from 95% to 70%. The powertrain performed as expected in terms of, e.g., speed-torque characteristics.

4 Discussion and Conclusions

Both the 96 VDC and 355 VDC electric powertrain were found feasible from the component availability and simulated performance point of view. Table 3 shows a comparison between the masses, volumes, and prices. As can be seen the low voltage variant is slightly smaller than the high voltage one. Also, the low voltage variant is less expensive than the high voltage one. Of course, in mass production the components could be further optimized, and costs decreased. Depending on the use case, both options could be viable, but for wireless charging, the high voltage system is a better fit.

Table 3. Comparison of the masses, volumes, and prices.

Component/powertrain	Low voltage	High voltage
Gearbox (mass / price)	11.3 kg / 1100 €	22 kg / 1500 €
Electric motor (mass / price)	42.7 kg / 1500 €	40 kg / 3500 €
Inverter (mass / volume / price)	2 kg / 3 dm^3 / 1200 €	10 kg / 13 dm^3 / 4400 €
Battery (mass / volume / price)	110 kg / 106 dm^3 / 10000 €	125 kg /148 dm^3 / 10000 €
Conductive charger (mass / volume / price)	8 kg / 12 dm^3 / 2600 €	8 kg / 12 dm^3 / 2500 €
Wireless charger (mass / volume)	-	14 kg / 8 dm^3

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Battery or Hydrogen Trucks: Assessing Truly Green and Cost-Effective Trucking Choice

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Abstract. Decarbonising heavy-duty truck fleets is essential for meeting the European Union's ambitious transport-related emission reduction targets. This paper presents the techno-economic and environmental modelling results of zero-or-low-emission truck fleets (ZLETs). ZLETs like battery electric and hydrogen fuel-cell electric trucks are compared against diesel truck fleets. Key parameters used to compare ZLETs against diesel trucks are total cost of ownership (TCO) and total carbon abatement (TCA) cost. TCO and TCA analysis are evaluated for three different electricity and hydrogen production scenarios: off-grid, on-grid, and hybrid (use of both dedicated renewables and grid electricity adhering to renewable energy directive-II). Results show TCO of both ZLETs is higher than diesel trucks for an off-grid scenario. Battery trucks show the lowest TCO for on-grid scenario due to the continuous availability of cheap grid electricity and no large-scale energy storage cost. In contrast, fuel-cell trucks are cheaper than battery trucks in a hybrid scenario due to the relatively low cost of large-scale hydrogen storage compared to electricity in expensive onsite batteries. Both ZLETs have minimum TCO for on-grid scenario. However, higher well-to-wheel emissions can be abated using a hybrid scenario. This shows only when cheap renewable electricity is available continuously without large-scale battery storage, battery trucks are more cost-effective and truly green choice over fuel-cell trucks.

Keywords: Heavy-duty trucks · Total cost of ownership · Total carbon abatement cost · Energy storage · Hydrogen · Renewable energy directive-II

1 Introduction

Movement of goods by road on heavy-duty trucks (HDTs) has grown significantly over the years due to globalization of trade and maturity of supply chains. While HDTs account for only 2% of total vehicle stock in the European Union, they contribute a quarter of greenhouse gas (GHG) emissions [1]. As of 2022, Ireland's road transport sector accounted for 19% of total GHG emissions with HDTs being the second most polluting segment after passenger cars [2]. HDTs are still heavily reliant on diesel fuel, representing a difficult-to-decarbonise sub sector. Several alternatives to diesel trucks (DTs) have been considered by the International Energy Agency, battery electric trucks (BETs) and

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hydrogen fuel-cell electric trucks (FCETs) appear to be the most promising zero-or-low-emission truck (ZLET) solutions when powered by renewably sourced electricity and hydrogen (H_2) [3]. As HDT operators have low-profit margins, total cost of ownership (TCO) is used for making purchasing decision between BETs and FCETs.

TCO studies have found BETs cost competitive with DTs for long travelling distances without accounting for payload penalty due to the overweight battery [4]. Long travelling distances above 500 km require BETs to have large batteries to complete their journey. Due to low battery gravimetric energy density, large batteries on BETs exceed the legal gross vehicle weight limit [5]. To comply with the weight limit, payload capacity needs to be reduced. This results in the need to add extra BETs to the fleet which needs to be fairly accounted for in the TCO analysis when comparing BETs with DTs. In terms of charging infrastructure, studies focus on fast charging, to reduce trucks battery weight and improve BETs competitiveness with DTs [4]. These studies neglect the need for large-scale energy storage and assume continuous availability of renewable based electricity to meet the BETs charging demand. There has not been an adequate investigation into how large-scale energy storage like onsite batteries, impacts the TCO performance of BETs.

TCO studies on FCETs have focused only on fuel supply systems that incorporate large-scale compressed tank H_2 storage [6]. Compressed tank H_2 storage has high specific capital costs, resulting in expensive H_2 fuel cost and higher TCO of FCETs compared to DTs. The effect on TCO by using different H_2 storage solutions like salt cavern and liquefied storage has not been sufficiently considered. In terms of using grid electricity for ZLETs, grid electricity needs to comply with strict spatial and temporal correlation rules [7]. Previous techno-economic studies have only considered these rules for hydrogen in FCETs, but not for electricity for BETs [8]. In this study, the impact of grid electricity rules based on renewable energy directive-II (RED-II) on TCO performance of both FCETs and BETs will be investigated and compared on an equal basis.

This paper addresses the literature gaps by performing modelling of: (1) zero-or-low-emission trucks considering their legal weight limit, (2) effect of large-scale energy storage on TCO of BETs, (3) impact of different H_2 storage types on TCO of FCETs and (4) effect of RED-II based grid electricity rules on TCO and total carbon abatement (TCA) cost of ZLETs. For this analysis, Ireland is used as a case study.

The objectives of this study are to (1) compare the TCO performance of ZLETs against DTs to find the most cost-effective trucking alternative, (2) assess the lifecycle well-to-wheel (WTW) GHG emissions of ZLETs to find a truly green trucking choice over DTs while considering the (3) TCA cost of each ZLETs. The next section describes the scenarios and methodology used for modelling TCO and TCA. Following that, results are discussed about the performance of ZLETs compared to DTs. Lastly, conclusion and future work are drawn based on this case study.

2 Scenarios and Methodology

This study evaluates the techno-economic and environmental performance of (1) battery electric trucks (BETs), (2) hydrogen fuel-cell electric trucks (FCETs) against (3) diesel internal combustion engine trucks (DTs) weighing 40 tonnes. Figure 1 shows the electricity and hydrogen supply scenarios considered in this study for BETs and FCETs.

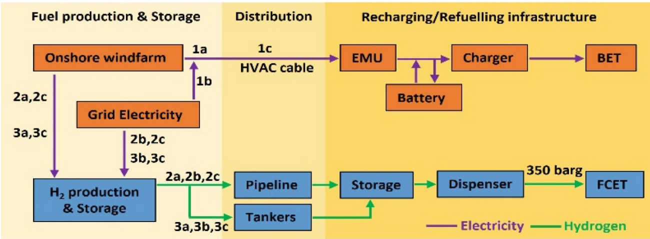

Fig. 1. Electricity and hydrogen supply for each scenario

In scenario 1a, electricity generated by an onshore wind farm (OnWF) is supplied to BETs through a no. of MW scale fast chargers during refuelling time. An onsite battery is used as energy storage to store surplus wind power when charging demand is low. During times, when wind generation is not enough to satisfy charging demand, onsite batteries provide electricity to the chargers as backup. In scenario 1b, all the charging demand is met by grid electricity and no battery storage is required. In scenario 1c, both wind and grid electricity (hybrid scenario) are used to meet the charging demand. In scenario 1c, grid electricity is only used when RED-II conditions are satisfied. The RED-II conditions state that hourly grid electricity can be used when: (1) electricity price is less than equal to 20 €/MWh and/or (2) emission intensity of the grid is below 65 gCO_2/kWh [7]. In scenario 1c, an onsite battery is used to store surplus wind and grid electricity satisfying RED-II to provide backup when wind generation is low and grid electricity is not accessible due to RED-II conditions.

In scenario 2a, electricity from OnWF is used for H_2 production, which is stored in salt cavern and delivered through a pipeline to a refuelling station. In scenario 2b, only grid electricity is used for H_2 production. In scenario 2c, both wind and grid electricity satisfying RED-II are used for H_2 production. Scenario 3 is like scenario 2 in terms of electricity supply for H_2 production with two key differences: (1) H_2 is liquefied, stored in liquefied tanks and (2) a tanker delivers liquefied H_2 to a refuelling station.

The hourly electricity generated from an OnWF is simulated using renewablesninja.com based on MERRA-2 dataset for an OnWF location near the port of Larne, Northern Ireland [9]. The hourly grid electricity prices and emissions are modelled by multi-variable regression analysis for a 2030 80% RES-E power system in Ireland. The weekly truck refuelling/recharging profile is taken from [10]. The significance of the methodology lies in the modelling of the hybrid scenario which represents a trade-off between TCO and WTW GHG emission of ZLETs.

2.1 TCO Model

Total cost of ownership (TCO) is used as a metric to compare the economic performance of ZLETs against DTs. TCO is calculated using Eq. (1) and represents the direct and indirect cost of acquiring and operating a truck over its lifetime. It has a unit of €/km. C_V is truck cost, C_M is truck maintenance cost, C_F is fuel cost, C_I is refuelling/recharging infrastructure cost, C_D is driver cost, C_{DT} is driver dwell time cost at the charging station, C_R is truck resale cost and D is total operational distance of truck. A bottom-up cost model was developed to calculate all cost components in Eq. (1).

$$TCO = \frac{(C_V + C_M + C_F + C_I + C_D + C_{DT} - C_R)}{D} \tag{1}$$

2.2 TCA Model

Total carbon abatement (TCA) cost is used as a metric to compare the environmental performance of ZLETs against DTs. TCA represents the cost of reducing a tonne of CO2 when switching from DT to ZLET for the same annual travelling distance on an emission basis. TCA is calculated using Eq. (2) and has a unit of €/tCO_2 abated.

$$TCA = \frac{(TCO_{ZLET} - TCO_{DT}) {}^{*} D}{\left(M_{WTW,DT} - M_{WTW,ZLET}\right)} \tag{2}$$

$M_{WTW,DT}$ and $M_{WTW,ZLET}$ is the well-to-wheel (WTW) emissions from DTs and ZLETs respectively. $M_{WTW,DT}$ is taken from [1] whereas $M_{WTW,ZLET}$ depends upon the hourly emission intensity of grid electricity.

3 Results and Discussion

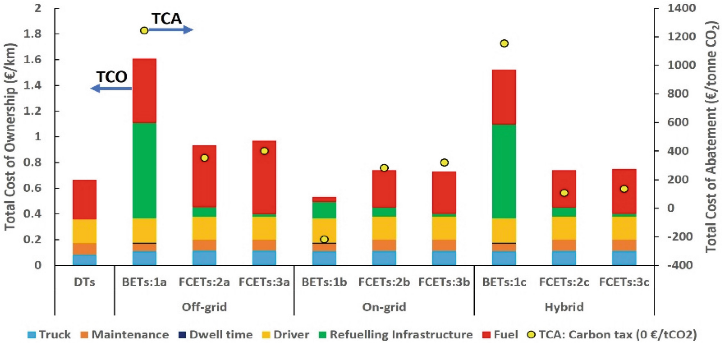

Fig. 2. Total cost of ownership and carbon abatement cost for heavy-duty trucks

3.1 TCO Analysis

The total cost of ownership for a fleet of 1000 trucks for all scenarios is shown in Fig. 2. Each truck has a daily travelling distance of 600 km which is based on a survey conducted amongst HDT operators in Ireland. Lower battery gravimetric energy density results in higher no. of BETs required in a fleet compared to FCETs. This leads to increased truck and driver costs for BETs. The maintenance cost of FCETs is higher than BETs whereas due to longer charging time only BETs have dwell time cost. In an off-grid scenario, big onsite battery storage is required as backup for meeting BETs charging demand. On the contrary, large amount of expensive OnWF electricity is required for H_2 production for meeting FCETs H_2 demand. This results in increased infrastructure cost for BETs and fuel cost for FCETs, resulting in both having higher TCO than DTs. Among grid scenarios, BETs have the lowest TCO (0.53 €/km) as grid electricity is continuously available to charge BETs, resulting in no requirement for expensive battery energy storage and reduced infrastructure cost. On the other hand, for FCETs due to the inefficiencies associated with H_2 production, more grid electricity is required. Leading to increased fuel cost and TCO compared to BETs. In hybrid scenario, only for a limited number of hours grid electricity is available to meet charging/H_2 demand. Electricity from OnWF and battery/H_2 storage are required to meet the remaining charging/H_2 demand. During grid electricity availability, a large amount of grid electricity is purchased and stored in batteries/H_2 to meet the future demands. But with increasing grid electricity in battery storage, battery size increases and onsite batteries become expensive. Beyond a certain battery size, any further cost reduction in TCO (1.52 €/km) is outweighed by increased battery storage cost. This leads to limited cheap grid electricity storage in batteries. Whereas large-scale salt caverns and liquefied tanks are a much cheaper form of energy storage compared to batteries and this allows for large amount of grid electricity to be stored as H_2 for future demands. The combination of buying cheap grid electricity (< = 20 €/MWh) and lower large-scale energy storage costs results in lower TCO of FCETs compared to BETs. TCO of scenario 2c and scenario 3c are 0.744 and 0.75 €/km respectively. TCO of scenario 3b (0.73 €/km) is lower compared to compared to 2b (0.74 €/km). This is due to the lower refuelling infrastructure cost as CAPEX and OPEX of pump and liquefied tanks are much smaller compared to compressor and compressed tanks at the station.

3.2 TCA Analysis

The total carbon abatement cost for a fleet of 1000 trucks for all scenarios is shown in Fig. 2. In an off-grid scenario, highest WTW emissions can be abated by ZLETs but at a significantly high TCA cost. For grid scenario, BETs (1b) has a TCA of -218 €/tCO_2 which is much lower than FCETs. This is primarily due to lower TCO and higher emission reduction by BETs than FCETs. On the other hand, for hybrid scenario, lower TCO difference between FCETs and DTs compared to BETs results in FCETs (2c and 3c) having a lower TCA of 107 and 136 €/tCO_2 than 1,155 €/tCO_2 of BETs (1c). Scenario 3 always has a higher TCA cost than scenario 2 due to the higher amount of electricity required for liquefaction, resulting in higher fuel cost and grid-based emissions. On-grid scenario has the lowest TCO for ZLETs but has the least WTW emission reduction when compared to DT. In contrast, a hybrid scenario reduces WTW emissions significantly while offering cost-effective TCO compromise for ZLETs.

4 Conclusion and Future Work

This paper evaluates the techno-economic and environmental performance for a fleet of (1) battery electric trucks (BETs), (2) hydrogen fuel-cell electric trucks (FCETs) against (3) diesel internal combustion engine trucks (DTs). Three different electricity and hydrogen supply scenarios were considered for BETs and FCETs: off-grid, on-grid, and hybrid. The performance of BETs and FCETs for each scenario was analysed based on total cost of ownership (TCO) and well-to-wheel (WTW) total carbon abatement (TCA) cost. In off-grid scenarios, both BETs and FCETs have significantly higher TCO and TCA than DTs due to energy storage infrastructure and fuel costs. In on-grid scenarios, BETs have the lowest TCO and TCA compared to FCETs due to the continuous availability of cheap grid electricity, no energy storage cost and higher emission reduction. On the other hand, for a hybrid scenario, FCETs have a lower TCO and TCA than BETs due to the relatively low-cost large-scale hydrogen storage compared to batteries during the unavailability of wind and grid electricity. Hybrid scenario enables ZLETs to achieve a cost-effective TCO while having a higher WTW emission reduction than an on-grid scenario. This study highlights that BETs are a more cost-effective and truly green choice over FCETs only when cheap renewable electricity is available continuously without the need for large-scale battery storage. Otherwise, FCETs are more suitable than BETs. Future work will investigate TCO and TCA performance of: (1) liquid H_2 trucks and (2) BETs when H_2 is used as energy storage instead of batteries.

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Transitioning Towards Green Port Operations: A State-of-Practice Approach on Emerging "Green" Technologies

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Abstract. This paper aims at providing a comprehensive review of the latest technologies developed within the context of EU funded projects, for the purpose of contributing to zero emission and carbon-neutral port operations. To identify the latest developments in a) technologies that enhance educated decision making; b) platforms ensuring seamless communication; c) technologies dealing with physical processes automation and d) technologies addressing energy management & GHG emissions reduction, the present review and evaluation incorporates a critical up-to-date analysis of the current leading-edge products and services in port operations. These advancements are identified in recent and upcoming EU funded projects and are described in trade journals and port-related industry sources of information. The impact of the developed technologies and solutions on the greening of operations and broadly on the port sector are demonstrated in an effort to highlight the rising technological tendencies. The present review also attempts to align these findings with the implementation of the key "green" technologies in ports, offering a state-of-practice approach.

Keywords: Low-emission · carbon-neutral port operations · port machinery · smart and "green" technologies · emerging trends · operational efficiency

1 Introduction

Although maritime transport is considered as an environmentally friendly mode of transport, it contributes to global emissions approximately 3% of the carbon dioxide (CO_2) emissions caused by human activities. At EU level maritime transport produced over 124 million tons of CO_2 in 2021 [1]. The International Maritime Organization (IMO) is taking effective actions that are necessary to achieve a substantial decrease in greenhouse gas

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(GHG) emissions from the shipping sector worldwide. To meet these emission reduction targets, major efforts will be required, including the development of new technologies and other initiatives to move the shipping sector to zero emissions. Ports undeniably play a significant role in the maritime sector's green transition due to their function as major nodes in the multi-modal transportation network, linking maritime transport with alternative modes of transport, but also as energy and innovation hubs.

This paper provides an overview of the technologies and tools that are being developed to improve port sustainability and contribute to the greening of port operations. The scientific literature contains a number of reviews on specific strategies, tools and measures implemented by ports to improve their energy and operational efficiency while minimizing their environmental footprint [2, 3]; policy frameworks to optimize port energy systems [4]; demonstrations of clean cargo handling technologies [5]; and techno-economic assessments of specific technologies and systems [6]. In this paper, the aim is to present a comprehensive review of the state-of-the-art technologies that are currently used in ports and terminals, with emphasis on their operational benefits and practical implementation.

2 Technologies

In assessing technologies to improve sustainability of port and terminal operations, the following challenges should be considered:

a) ensure that past experience can be properly exploited, building a solid background to support educated decision making in the greening of the port sector at an operational, tactical and strategic level.
b) ensure seamless and effective communication among relevant stakeholders, in order to optimize and synchronize operations and achieve reduced environmental impact.
c) automate physical processes and ensure proper interface between the various port subsystems that have been automated or between automated and non-automated subsystems with the aim of optimizing these processes and achieving reduced environmental footprint.
d) minimize the energy consumption and environmental impact both as a standalone practice as well as in conjunction with the previous three essential areas of sustainability intervention.

Along this line, a summary of relevant indicative technologies is presented next.

2.1 Technologies Enhancing Educated Decision Making

Artificial Intelligence and Machine Learning in Port Operations. Depending on the type of port and its traffic, AI technology could be provided as an integrated tool to predict vessel traffic, improve berth planning, and optimize the efficiency and productivity of maritime operations [7]. The port of Los Angeles is currently utilizing AI applications, using data from sensors installed in terminals and machine learning algorithms to predict the arrival of ships in ports and optimize the loading and unloading processes by planning and coordinating the related port operations. The Port of Singapore uses an artificial intelligence system and natural language processing for customs and immigration control processes, analyzing and categorizing the data derived from documents related to shipping and customs [8]. **Internet of Things in Port Operations.** The IoT system may serve as a basis for ports to achieve greater levels of operational efficiency and reduce the overall operating cost, as well as minimize their environmental footprint. Furthermore, access to the collected data from installed sensors in the port area enable the detection of potential accidents and threats (e.g. fire detection) in the port, and thus, enhance safety and security**.** As an example, the Port of Rotterdam in collaboration with relevant stakeholders, has developed an IoT platform to promote the safety and operational efficiency in port activities [9]. **Digital Twins**. By combining the visual and physical attributes of a port area, the operations are significantly improved in terms of efficiency. For the port of Rotterdam, the intelligent berths allow the port manager to foresee the risk of collision by combining historical berth data with local weather information [10].

2.2 Technologies and Platforms Ensuring Seamless Communication Along the Transport Chain and Supporting Players' Collaboration

Blockchain Technology. A great variety of stakeholders are engaged in port operations, such as shipping and trucking companies, customs agencies, and governmental organizations, all of which have their own procedures, documentation, and data requirements. This complex configuration frequently causes delays, errors, and operational bottlenecks. However, with the use of blockchain technology, all parties may gain access to up-to-date information, including cargo status, port clearances, and customs documentation, which assists in mitigating these problems [11].

2.3 Technologies Dealing with Physical Processes Automation

Automated Terminal Equipment. Automated straddle carriers seem to meet the requirements of terminal automation, as they are able to operate independently in different conditions. The port of Aarhus has been equipped with automated straddle carriers that were developed in accordance with its specific characteristics, leveraging insights from the yard operations [12]. The Automated Rubber-Tyred Gantry (ARTG) systems provided at PSA Sines are able to improve the efficiency, performance predictability, and safety of the terminal, supporting and facilitating the terminal's expansion plans. Container stacking is managed by the Remote Operating Station (ROS) [13]. **Autonomous Vehicles.** The large and technologically advanced ports are already preparing for the arrival of autonomous vehicles in order to remain competitive in the port market. The Jebel Ali Port is an example of a port that is preparing along this line and which has deployed a fleet of Autonomous Internal Terminal Vehicles (AITVs) in its terminals. **Unmanned Aerial Vehicle (UAV) – Drones**. The use of data-gathering drones is an increasingly anticipated approach that is expected to become a common practice in the near future. These intelligent, self-driving drones have been designed to, among other things, automatically find ships and small vessels at sea, sample pollutants using onboard sensors, and send the collected real-time data in a secure and cost effective manner.

2.4 Technologies Addressing Energy Management & GHG Emissions

Decarbonizing Port Terminal Equipment. The electrification of terminal equipment is a rather wide-acknowledged practice that contributes to the emissions reduction, lower fuel consumption and decrease maintenance costs in terminals. Retrofitting or replacing the current diesel-powered equipment in ports (forklifts, straddle-carriers, prime movers, lift trucks, terminal tractors, rubber-tired gantry cranes (RTGs) and mobile harbor cranes (MHCs)) with electric propulsion systems is an energy efficient and cost-effective way to reduce emissions from cargo handling in port operations [14]. **Alternative Fuel-Powered Supporting Vessels**. To promote greener operations in port areas, emphasis has been placed on the greening of the port fleet, which includes tugs, dredgers, support vessels, etc. [15]. **Shore Side Electricity-OPS.** The currently available shore power technologies provide a range of opportunities to the ports and terminals as well as to the ship-owners. Retrofit plans for older vessels and on-board power solutions meet the operational challenges of the fleets and include a total system approach. For the new built ships, the solutions developed by the technology providers include products with different power levels, cable lengths and installation options, depending on the specific requirements, thus increasing operational efficiency and providing a flexible solution for each vessel. The state-of-the-art technology includes fibre optic connectors, self-propelled and battery-operated units that recharge the ship even if the vessel's cables fail to extend towards the charging unit, portable systems that can be easily transported by truck, autonomous implementation with no civil works requirements at berths and enhanced operational safety accomplished through radio remote control systems [16, 17].

3 The Impact of Developed Technologies on "Greening" of Port Operations

Technologies can significantly contribute to the greening of port operations by increasing productivity, reducing environmental impact and promoting sustainability. Table 1 provides an overview of the trending technologies being, or soon to be, implemented, emerging from recently launched EU funded projects. As it can be seen from the analysis in Table 1, special attention has been given to technologies that enhance educated decision making and technologies that may be used to address the energy management and GHG emissions at seaports. There are several ways in which these technologies can be applied to make port operations environmentally friendly, including the following: a) data analysis and predictive modelling contributes to the optimization of port operations by predicting the vessel's arrival times, improving their shipping routes and efficiently handling the cargo flows within port, ultimately reducing the fuel consumption and exhaust emissions; b) automated, robotic cargo handling and autonomous vehicles can improve the efficiency of port operations, reduce costs and lead to more accurate and greener cargo handling; c) environmental monitoring systems to facilitate the monitoring of air and water quality in ports, identify the areas for improvement and comply with environmental regulations; d) Blockchain technology for transparency, enables the improved tracking of goods and can be particularly relevant in tracking the origin and sustainability of goods being handled in the port; e) Shore Side Electricity-Onshore Power Supply supports the air pollution and GHG emissions reduction.

In addition to the ongoing projects and technology development and implementation initiatives, several new priorities are planned to be supported through the EU research as well as national programs.

By using a combination of these technologies, ports can not only become more environmentally friendly, but also improve the overall efficiency and sustainability of their operations. A successful implementation of the technologies demonstrated in this paper, frequently requires the cooperation between various port-related stakeholders such as government agencies, port authorities, shipping companies and technology providers.

Table 1. List of EU funded projects and the four pillars of technologies

Acronym of EU funded Project	Technology	Status	Technologies enhancing educated Decision Making	Technologies & Platforms ensuring Seamless Communication along the Transport Chain & enhance Players' Collaboration	Technologies dealing with Physical Processes Automation	Technologies addressing Energy Management & GHG Emissions
DataPorts	Blockchain technology	Finished		X		
PIXEL	IoT platform	Finished	X			
ForFreight	Decision Support Systems based on Digital Twin, Blockchain technology	Ongoing	X	X		
TRUST	autonomous ships	Ongoing				X
COREALIS	*Internet of Things, 5G instruments, data analytics, next-generation traffic management*	Finished	X			
RCMS	*state-of-the-art container handling technologies*	Finished	X		X	X

(*continued*)

Table 1. (*continued*)

Acronym of EU funded Project	Technology	Status	Technologies enhancing educated Decision Making	Technologies & Platforms ensuring Seamless Communication along the Transport Chain & enhance Players' Collaboration	Technologies dealing with Physical Processes Automation	Technologies addressing Energy Management & GHG Emissions
AUTOSHIP	*next-gen autonomous ships*	Ongoing			X	X
ENDURUNS	*Hydrogen fuel cell-powered AUV*	Finished			X	X
DT4GS	*Digital Twins*	Ongoing	X			
CRANES	*Inspect monitoring and prevention system*	Finished	X			X
C-BORD	*innovative detection technologies*	Ongoing	X		X	
PortsH2Ports	*Terminal equipment powered with hydrogen*	Ongoing				X

Furthermore, exchange of knowledge and experience among port stakeholder groups may accelerate the efficient uptake of new technologies.

4 Conclusions

This paper presents a comprehensive review of the latest technologies emerging from EU-funded projects, with a focus on promoting zero emission and carbon neutral port operations. Through detailed examination of recent and upcoming projects, the study identifies cutting-edge developments in technologies that enhance informed decision-making, ensure seamless communication, automate physical processes, and address energy management and greenhouse gas (GHG) emissions reduction. The critical analysis of these technologies incorporates insights from trade journals and industry sources, providing an up-to-date overview of leading products and services in port operations. The impact of these technological advances on the greening of operations and the wider port sector is critically demonstrated, highlighting evolving technological trends. In addition, this review attempts to align its findings with the implementation of key 'green' technologies in ports, presenting a state-of-practice approach. By synthesising information from different sources, the paper not only provides a summary of the current technological landscape, but also offers valuable insights into the transformative potential of these innovations for achieving environmentally sustainable and technologically advanced port operations in the European context.

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Improving Transport Performance and Decarbonization Potential in Small-Medium Ports

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Abstract. Port areas play a key role in the economic well-being of modern societies by facilitating trade, creating jobs, generating revenue, improving sea transport efficiency and promoting regional development. One of the biggest concerns associated is related with high levels of greenhouse gases emissions. The present work aimed at quantifying the emissions generated by several mobility alternatives (road, maritime and rail modes) carried out in Aveiro and Figueira da Foz ports, located in the Centre region of Portugal and propose a Mobility Decarbonization Plan in small-medium size Ports. PTV VISSIM microscopic model was used to assess vehicles flows to/from/inside the Ports. Using the methodology EMEP/ EEA, the results indicate that 19 600 t and 6 750 t of CO_2 were emitted in Aveiro Port, and 4 900 t and 1 900 t of CO_2 emissions in Figueira da Foz Port for the years 2022 and 1990, respectively. Subsequently, alternative scenarios concerning alternative fuels, electrification and intermodality were analyzed. Among the measures studied with the greatest potential for reducing CO_2 emissions are onshore power, electrification of cargo handling equipment, cargo modal shift from road to rail transport and the use of B100 as alternative fuel. Finally, the mobility decarbonization plan based on the alternative scenarios was designed.

Keywords: Small-medium Seaports · Mobility · GHG Emissions · PTV VISSIM · EMEP/ EEA

1 Introduction

Ports are spaces with infrastructure that allows ships to dock, load and unload goods, and embark and disembark passengers [1]. They are therefore considered multimodal nodes, where goods are transferred between different modes of transport, such as sea, rail and

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road. Thus, port activities are not limited to maritime transport, and there are various sources of environmental pressure in the area, namely road and rail transport. According to studies, the most polluted cities are in coastal areas, aggravated by the fact that around 70% of maritime emissions occur up to 400 kms from the coast. The pollutants emitted are easily transported to cities on the coast, causing health risks for inhabitants and a deterioration in local air quality [2–4]. While there are several sustainability reports and inventory of greenhouse gases (GHG) emissions for ports (e.g., [5, 6]), some energy transition roadmaps for the port environment [7], there are few ports stablishing targets and guidelines for decarbonizing mobility (e.g., [8]).

Thus, the main objective of this paper is to study the impact on GHG emissions of a set of strategies to implement them in a mobility decarbonization plan for a small and medium-sized port area. The study area will focus on the Ports of Aveiro and Figueira da Foz, in the Centre region of Portugal. To achieve the main objective, the environmental pressures were first assessed, particularly the GHG emissions resulting from mobility activities in the ports. After the GHG emissions in the ports under analysis were quantified, several scenarios were established. In the end, a decarbonization plan with concrete measures was designed and proposed.

2 Methodology

2.1 Case Study

This section aims to describe the scope of the work, which is directed to two study areas, the Ports of Aveiro and Figueira da Foz. The case study focuses on the quantification of GHG emissions arising from port mobility activities in 1990 and 2022.

The Port of Aveiro has 7 specialized terminals (North, South, Solid Bulk, Liquid Bulk, Container and Ro-Ro Terminals, Coastal and Long-Distance Fishing Ports) and 1 intermodal logistics zone. In 2022, there was a movement of about 5.78 million tonnes, with the entry of 1 053 vessels. The total volume of cargo consisted of 38% dry bulk, 36% general cargo and 26% liquid bulk. The Port of Figueira da Foz has several areas in its facilities: Recreational Dock, General Cargo, Solid Bulk and Liquid Bulk Terminals, Coastal Fishing Harbor and the logistics zone. In 2022, a total of 2.2 million tonnes were handled, with 536 vessels recorded. In this case, the cargo distribution consisted of 48% dry bulk, 44% general cargo, 7% containers and 1% liquid bulk.

2.2 Transport Flow Modelling and GHG Emissions Calculation

This section aims to present the methodology used for modelling and simulating the activities of rail and road modes. The software selected was PTV VISSIM [9]. VISSIM simulates the behaviour of individual vehicles and their interactions on a given transport network. For both ports, it was assumed that the cargo was moved to the proximity of the vicinity of the place where it was subsequently placed. The modelling of the railway mode aimed to simulate the railway activity from trainsets consisting of combustion engine locomotives. The road mode supports movement of cargo and workers. Its modelling aimed to simulate the flows of passenger cars and heavy goods vehicles operating on a typical working day, between 6am-9pm. It was possible to analyze about 91 km of roadway for the Port of Aveiro and 25 km for the Port of Figueira da Foz. Once the network modelling was completed, driving behavior was depicted from speed reduction and speed limitation zones. The model was calibrated and validated [10].

Regarding emissions, the methodology selected was EMEP/ EEA, authored by the European Environment Agency [11]. To quantify CO_2 emissions from ships activity in both ports, Tier 3 equations were used. The emission factors were obtained from the ENTEC manual (2010) [12]. In the case of vessels, the calculation used the equation of Tier 1, based on average fuel consumption. For rail, the quantification of CO_2 emissions from combustion train activity was based on Tier 3 [5]. For operational reasons, the port terminals do not have catenaries inside them, so all the activity of handling electric locomotive wagons is carried out using shunting locomotives. The quantification of CO_2 emissions from the operation of the locomotive by Tier 2 was possible from fuel consumption data in each port, 4 725 l and 4 571 l consumed in Aveiro and Figueira da Foz, respectively. The road mode includes passenger car and heavy goods vehicle activity. Initially, the energy consumed (MJ/kWh) was obtained as a function of the average speeds of the vehicles, using the Tier 3. Next, CO_2 emissions are calculated from the relationship with the fuel consumption [11]. Finally, non-road cargo handling equipment are elements that allow cargo handling operations to be carried out. The quantification of CO_2 emissions was based on Tier 2 and 3 equations, assuming diesel consumption.

2.3 Alternative Scenarios

This section aims to implement scenarios on alternative fuels, electrification and intermodality. These consider emission factors based on life-cycle analysis of different energy vectors [13]. For alternative fuels, hydrogen, methanol and biofuels were studied. The first two were implemented in the activity of ships. Biofuels were implemented in ships, vessels, road mode and port equipment. For electrification theme it was analyzed scenarios where electric power is applied to ships, in their berthing phase, to the road mode and to port equipment. The topic of intermodality aims to analyze scenarios where the concept is applied to 4 scenarios: extrapolation of 30% and of 50% of the cargo handled by road to rail, and implementation of 750 m trains with daily and tri-daily operations (percentages intended to fulfil the objectives of the Portuguese National Railway Plan).

3 Results and Discussion

This chapter presents the inventory of CO_2 emissions and the reduction potential in the Ports of Aveiro and Figueira da Foz calculated through EMEP/EEA methodology. The emissions analysis section aims to portray the GHG emissions inventory prepared for the mobility activities of both port areas, in the years 1990 and 2022. The complete inventory of CO_2 emissions is shown in Table 1. From the observation of the Table 1 it is remarkable the contribution of the maritime mode to the GHG emissions of both ports. The contribution of this mode to the GHG emissions of the ports in 2022 is in the order of magnitude of the values of the literature (44%, 87%, 33–62% and 46%) [4, 14].

Table 1. Inventory of CO_2 emissions in 1990 and 2022

Port	Aveiro				Figueira da Foz			
Mode	2022	%	1990	%	2022	%	1990	%
Maritime	12 377 *t*	62.7	6 753 *t*	90	3 505 *t*	71.4	1 754 *t*	92
Rail	23 *t*	0.1	-	-	18 *t*	0.4	-	-
Road	2 894 *t*	14.7	445 *t*	7	258 *t*	5.3	71 *t*	4
Handling equipments	2 256 *t*	22.5	214 *t*	3	1 126 *t*	22.9	82 *t*	4
TOTAL	19 750 *t*	100	6 753 *t*	100	4 906 *t*	100	1 907 *t*	100

In 2022, CO_2 emissions from ships and pilot boats were quantified in maritime mode. CO_2 emissions from tugboats and fishing vessels were also estimated. Table 2 shows the obtained results. To validate the results obtained for CO_2 emissions at the time of berthing, it was possible to conclude that the contributions of the respective phase to the GHG emissions of ports, in the same order of magnitude as the values described in the literature (50- 80%) [4, 14].

Table 2. Inventory of CO_2 emissions for maritime transport in 2022

Type	Phase	Aveiro	Contribution	Fig. da Foz	Contribution
Ship	Manoeuvres	1 045 t	5.3%	272 t	5.5%
	Berth	10 118 t	51.2%	2 744 t	56.0%
Pilot boat	Manoeuvres	92 t	0.5%	16 t	0.3%
Tug boat	Manoeuvres	624 t	3.2%	291 t	5.9%
Fish boat	Manoeuvres	496 t	2.5%	181 t	3.7%

Figure 1a represents the CO_2 emission reduction potential for different alternative fuels for certain percentage levels of penetration (namely 30% of biodiesel in diesel – B30) within the fleet of ships while Fig. 1b) focus on electrification scenario. When it comes to electrification, the intention of port entities is to invest in the production of renewable electrical energy, allowing its supply to equipment operating in the facilities. In this way, measures were suggested that aim to replace conventional models with electric models (heavy duty vehicles – HDVs and ships).

A path of possible measures to be implemented was established, aiming at the goals set by the port authorities. The measures defined were based on the alternative scenarios previously studied, to be considered the life cycle analyses of the different energy means and the affected fleet. On the other hand, for the years 2025 and 2030, emission factor values were defined based on the claims outlined in the National Energy and Climate Plan 2021–2030. It is also important to highlight the project of the Port of Aveiro with a view to producing 7 GWh per year, by 2030, of renewables [7]. From the inventories of ship entries in 2022, the years of the models that had activity were analysed. Considering

(a)

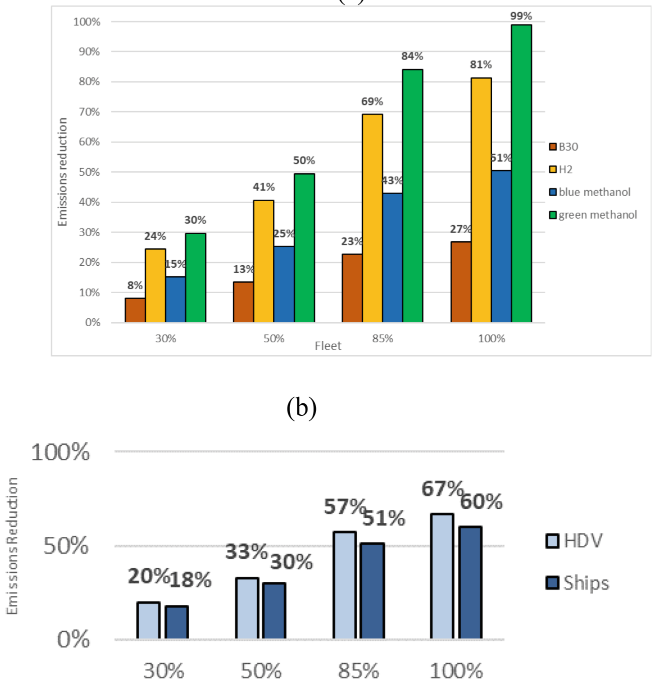

Fig. 1. Emissions of CO_2 reduction potential for: a) alternative fuels in ships; b) electrification.

a useful life of 25 years, the data allowed to predict the replacement of conventional ship models by alternative solutions. Decarbonization measures were assessed for the years 2025, 2030, 2040 and 2050.

Figure 2 shows global emission reductions predicted for 2025, 2030, 2040 and 2050.

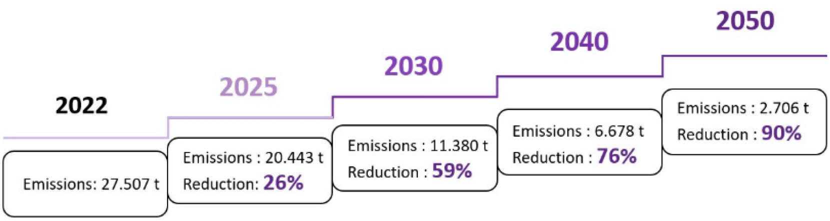

Fig. 2. GHG Emissions reduction with the implementation of a mobility decarbonization plan

4 Conclusions

This work aimed at defining a mobility decarbonization plan based on new scenarios assessed with prospects of gradual technological evolution in the medium and long term. Based on the measures implemented, it is justified the need to increase the share of renewable energies in the electricity generation system, to make it possible to reduce GHG emissions. In this case a challenge will be the annual production of electricity to meet the needs of transport modes. In short, the decarbonization of the port sector requires more sustainable approaches throughout the life cycle of the energy resources used. New paradigms need to be applied along the entire chain and enable cost-competitive commercialization compared to conventional fuels.

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Ports as Urban Transition Actors Towards Zero-Emission Transport

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Abstract. The transition to sustainable mobility and zero emission transport requires clear visions and engagement from actors with agency to influence and drive transition processes. Ports can be such actors, contributing to the development and diffusion of innovative zero emission and low carbon solutions in transport both on land and at sea. It is however still not clear how ports should act to reach such goals, and sustainability practices of ports are still largely understudied. This paper discusses how to strengthen energy and sustainability transitions and the capability of ports to engage in such transitions through co-creation of transition agendas, visions and role development. The paper demonstrates how ports themselves, if acting as urban community managers may drive transitions in zero-emission transport and how sustainability transitions as a result can become both wider and deeper, which is needed for the Net Zero transition to happen. The paper builds on studies of three Norwegian ports, transition management exercises in these ports and interviews with port actors in Norway.

Keywords: Ports · Transitions · Zero-emission transport · Policy · Urban actors

1 Introduction

1.1 Ports as Sustainability Transitions Actors

Ports and harbors have historically played a central role in urban environments, as infrastructure nodes connecting land and sea-based transport of both goods and people. Many of the world's largest cities are also founded because of them being strategic harbors. Still, the role of ports has been largely ignored when discussing the key challenges such as climate change and sustainable urban development.

This paper is based on the ACES project where the aim is to explore how ports may take more proactive roles in the sustainability transition including energy and transport. Building on insight from sustainability transitions research, we have explored the potential of ports to become transition actors that may accelerate transitions. By use of action-oriented methods as descried in the Transition Management (TM) literature [1] we have strived to increase the capability of ports to engage in driving such transitions

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through co-creation of transition agendas, visions and role development. As nodes in transport systems, ports may shape and transform the energy use in the three domains intersecting: the port domain, the sea transport domain, and the hinterland transport domain [2]. This paper particularly focuses on ports as actors driving urban transitions towards zero-emission transport.

Research on port governance and sustainability has grown during the last years and provides some, yet limited, perspectives on how ports may be governed in more sustainable directions. The Norwegian government has declared that all domestic ports should be zero-emission by 2030. National targets are, however, not enough as emissions continue to grow despite ambitious goals. Reviewing 70 articles exploring potential measures for mitigating emissions connected to port operations, Bjerkan and Seter [3] found more than 26 available tools and technologies, demonstrating the existence of a plethora of potential low emission technologies that may be used. Less attention has been given to how port decision makers may incentivize, implement, prioritize, and decide which technologies to implement. Consequently, Bjerkan and Seter [3] suggest directing the attention towards how to engage port actors and ways to develop their agency in sustainability transition processes so that they may drive changes towards low-emission transport. Previous research has also demonstrated that the port domain, the sea transport domain, and the hinterland transport domain differ to what degree port actors succeed in identifying a particular pathway towards transition (e.g., electrification) and whether they see themselves as having the capacity to intermediate processes that could lead to such changes [4]. Bjerkan et al. [2] identified that ports that took on roles as community managers also acted in an intermediary role linking intermediation activities with more progressive transition work. In sum, a focus on how to nurture and empower port actors to govern transition processes towards more sustainable systems including zero emission transport is needed.

2 Methods

Transition Management (TM) is a prescriptive framework [1] which enables policy makers to nurture and govern transitions through strategic, tactical, operational, and reflexive activities [1]. TM recognizes that transitions do not come about through a top-down process, but by interactions among a plurality of actors through which actors are empowered to reach sustainability goals by challenging, transforming, or replacing existing socio-technical regimes [1]. At the core of TM lies Transition Arenas (TA), which bring together actors from science, policy, civil society, business, and industry to foster collaboration and visions that enable and accelerate transition work.

In the study, three local transition arenas were created following the approach of Notermanns et al. [5] in relation to three ports; the Port of Bodø, Port of Borg and Port of Kristiansand. An actor and a system analysis were conducted before a transition team consisting of frontrunners and a broad range of stakeholders was established. In the TA participating actors created a vision and future pathways and means to get there were co-created through backcasting exercises. In the following, findings from the TM process are reported, using the Port of Bodø as an example. Findings from the other two ports are used to show nuances or contrasts where relevant.

3 Empowerment Through Transition Management

The developments in the Port of Bodø could be summarized as a shift from incremental change to transformative reorientation. This shift is apparent in the expansion of visions, the widening of networks, and the reorientation of fundamental perceptions. These developments – visions, networks, and reorientation – are considered core processes of sustainability transitions [6] and will be elaborated further in the following.

3.1 Renewed Visions

Firstly, TM in the Port of Bodø was accompanied by a renewal of visions for the future. Visions, or expectations, represent shared perceptions about how the future could (or should) be. Transitions scholars (e.g. [6]) argue that shared perceptions provide a navigation tool, by which actors can direct technology searches, initiate collaboration and mobilize resources. As a shared venture point, visions install a certain legitimacy in actions that support the realization of co-developed ideas of the future.

The TM process in Bodø displayed a clear shift in the vision-making of the port. Initially, the port's vision focused on the terminal project, connecting the port to "the development of a modern and forward-looking multimodal freight hub". This vision derived from the port's work with designing a new logistics terminal for more efficient handling of goods and person traffic. This ´terminal project´ was already initiated to strengthen the Port of Bodø's position as a logistics and mobility hub for the region and could be seen as contributing to incremental change. An essential element of the TM process is however, enabling vision-making through identifying ways in which alternative futures could remedy fundamental challenges facing the actors. By discussing challenges pertaining to the continued development of the port, stakeholder involvement in TAs produced an increasing recognition of port development as an aspect of broader societal change. For the Port of Bodø, this implied recognizing how their own challenges were connected to developments far beyond their terminal and daily operations and a shift from short-term challenges and near realization solutions (such as how to implement low emission port solutions) towards more visionary thinking, looking for ways to contribute to longer term goals. Through co-creation workshops, actors related to the port developed a new vision seeing Port of Bodø as "a cornerstone of sustainable development" where the port was seen as an engine for industrial and sustainable development in the region, encompassing both energy and transport systems: an energy positive zero emission hub and an important logistics and preparedness center in the Nordics.

3.2 Expanded Networks

The TM processes also included a shift in the port's building and utilization of social networks. Social networks are crucial components of transition processes because they represent a pool of resources that actors can draw on to pursue and protect innovation and engage in collective action [7]. The building of social networks are important aspects of transition work because the broadening of networks gives access to different and complementary resources and because building strong and committing relations enhance the ability to initiate and follow through with actions.

In the Port of Bodø, the TM process enhanced both the actor diversity and the level of integration in the port's network, which is a typical characteristic of high-performing networks. The early phases of the process mainly involved actors relating to port operations and the logistics terminal. A broad spectrum of stakeholders was however invited and included into the TAs. The actors were logistics operators, industry, and cargo owners and as the TM process proceeded, an increasing number of actors were attracted to the arena, thus representing an increasingly complex and broader set of perspectives than had initially been the focus of the port. The final arena meetings also included actors representing the regional development council, tourism, and national environmental NGOs. The expanded network also spurred concrete activities such as the municipality taking part in new projects. Also, the port became interested in how to embed politicians, as well as other (previously unidentified) stakeholders and actors in future developments and plans to develop the region. Thus, how to organize cooperation between different institutions in a new way was made key to the transition process.

3.3 Normative Reorientation

Finally, the TM processes produced knowledge that altered the port's perception about its own place and role in the systems of which it is part. Learning processes are key in sustainability transitions because they enhance our understandings of technologies and innovations for decarbonization, as well as aspects that support their successful implementation, such as regulations, impacts, market potential and user acceptance [6]. Hence, network building could enable learning because it secures access to different types of expertise. However, for learning to produce more transformative action and change, transition scholars argue that it needs to induce a fundamental reorientation of institutionalized assumptions, values and world views that are currently taken for granted (e.g., [8]) – A type of unlearning that allows an individual or group to develop novel perspectives, skills, and practices.

During TM processes in the Port of Bodø, we saw examples of reorientation of perceptions. Such reorientation largely revolved around how the Port of Bodø started to perceive itself and its operations as part of a larger socio-technical system, moving from its traditionally operational and commercial raison d'être. As evident from its vision, the port stated to consider itself "a cornerstone", "a building block" and "an engine" driving desirable and required changes in the region. This implied that the port renewed its idea of own potential interaction with its surroundings, expressed in a more holistic understanding of the needed dynamics for it to foster industrial and regional development and tourism.

Thus, we observed how learning processes changed role perceptions in the Port of Bodø, which also had a direct impact on the ways in which the port worked to integrate its network. The port increasingly took on the role as a community manager that engages relevant stakeholders in the process of establishing funding and support for a new solution deemed necessary to connect sea and land transport in a better way. This renewed perception of the port's role evolved from aspects of the TM process in which TA participants deliberated on ways to develop future transitions pathways, specifically identifying what aspects of existing socio-technical systems should be retained, phased out, or supported to transform the sociotechnical port system in the desired direction.

During the TM processes, three pathways were identified as particularly important, and they all rested on the port's renewed sense of responsibility for facilitating better ways of cooperating with other actors to ensure manifestation of these transition pathways. Hence, by engaging in TM, the port became part of a broader societal change process, which enabled the port of Bodø to increasingly see their own role as a community developer.

Similar transitions dynamics also manifested themselves in the other two ports because of the transition management process. In Borg the normative reorientation was particularly evident as the port identified the need for formalizing a new role related to industry coordination.

4 Concluding Discussion

The analysis reveals that it is not only the port actors´ abilities and capacity to drive socio-technical change processes that develops due to applying a TM approach. The nature of the transitions that the actors drive also seem to change; the transitions become *broader*, spanning system boundaries, and *deeper*, targeting more fundamental elements of the transport system (in line with new needed directions of the Net-Zero transition (see eg., [9]). Thus, we see a shift from incremental changes - from focusing on implementing single low emission solutions in energy and transport systems to focusing on real transformative systemic changes that more fundamentally target the broad spectrum of stakeholders and institutions.

The TM methods, thus, demonstrates that ports may become important transition drivers towards low emission transport when transition agendas are co-created with a broad number of stakeholders, as this seems to create long term shared visions that target the regime (the systemic level) rather than focus on incremental change. This seems to add to the intermediary role of ports as a role they cannot do alone but is dependent on collaboration precisely because of their node positions between different sectors and stakeholders.

Existing visions, policies and regulations may contribute to drive transitions. However, they are seldom deeply anchored in related domains and practices outside the policy domain and often do not contribute to more systemic changes needed for the system to transform in a more sustainable direction. Developing roles so that more actors experience agency and commitment towards driving transitions in the same direction is central to this.

The paper demonstrates that ports can be key urban transition actors towards zero-emission transport in interaction with a broad number of actors, all empowered to reach sustainability goals by challenging, transforming, or replacing existing socio-technical regimes. The paper points to how working systematically with TM may give port actors new ways of working strategically with transition dynamics that could have both wider and deeper systemic impacts for sustainability transitions beyond the port domain. The paper demonstrates that coordinated alignment and actions of a multitude of port related actors are needed for transitions to zero emission transport in ports to evolve and for urban ports to act as enablers for transitions to zero emission transport. Creating arenas where actors from different sectors meet to focus on co-creating zero-emission transition pathways may be seen as a successful tool to accelerate the transition in ports and beyond.

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Hydrogen and Battery Trains, Which Technologies for Future Light Trains?

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Abstract. Even if rail transport is a low carbon emission mode of transport, 20% of rail operations are done by diesel traction in France. SNCF, the French historical railway operator, is investing in the decarbonization of the fleet with the development of hydrogen and battery trains, which present different performances than current diesel or electric rolling stocks. By using a dedicated simulation tool, this paper addresses the diversity of line profiles and operating constraints of a light train with battery and hydrogen traction to map area of relevance and to define the energy and power requirements. It results that there is no one-size-fits-all solution to decarbonize rail transport. Both battery and hydrogen technologies have their relevance in secondary rail networks depending on the technological solutions, infrastructure, and desired transport service.

Keywords: Battery · Hydrogen · Light Train · Railway · Simulation

1 Introduction

The SNCF group has undertaken to end its direct emissions by 2050. Achieving this goal implies the need to decarbonize the fossil thermal fleet by switching its drive chain to renewable energy sources.

Battery and hydrogen-based electric traction are today regarded as very promising diesel alternatives. However, various solutions at different maturity levels and development stages coexist. Systems built today with a certain technological choice and maturity will have to be sufficiently modular to be able to embrace other incoming technologies, possibly non-existent during their implementation or even belonging to another technological family. Therefore, it seems relevant that future trains can accommodate several technologies in a modular and standardized way, which implies multi-partner collaborative development. In this way, a French consortium "*Train Léger Innovant*" (TLi), which brings together industrial and academic stakeholders, has been established in 2022 with the financial support of ADEME, the French Agency for Ecological Transition.

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The complexity of infrastructure adaptation using hydrogen and battery technologies remains uncertain and highly variable due to cost, time, regulation considerations, etc. It must be compared based on a case-by-case approach. The relevance of each technological variant must therefore be assessed over its entire life cycle, by territory and by integrating the rates of rise in maturity conditioned by other applications. Other factors may be considered like anticipating regulatory changes, scale effects, the evolution of the transport offer as well as the obsolescence management. Adopting this system approach is crucial in this regard as it offers an innovative solution that reconciles the need for a long-term stable operational train with the adaptability to fast-evolving technologies.

The objective of this paper is to address the diversity of line profiles and operating constraints of a light train with battery and hydrogen traction to define the energy and power requirements. The challenge is to assess it for the entire secondary rail network (UIC 7 to 9 SV: defined by the International Union of Railways) and based on an existing transportation plan currently in place. The expected results are the definition of relevant areas.

The outline of the paper is organized as follows. Section 2 describes technological decarbonization solutions, Sect. 3 describes the used methodology, Sect. 4 presents train parameters and simulation assumptions. Section 5 is focused on simulation results. This will lead to discussions and conclusions.

2 Technological Solutions

Four technological families have been identified as relevant by SNCF to decarbonize rail transport: line electrification, non-fossil liquid fuels, batteries, and hydrogen.

Electrification involves installation of new catenaries. This family is the most energy efficient and the least carbon-intensive due to the French energy mix. Electrification, however, is expensive and takes a long time to implement.

Non-fossil liquid fuels are produced from organic matter or waste oils. They maintain local emissions of GHGs and pollutants despite a significantly reduced well-to-wheel GHG balance compared to diesel. Biofuels are considered as a transitional solution and are therefore not retained as part of a project to acquire new trains given SNCF's objective of reducing its direct emissions to zero by 2050.

The particularity of the battery family is the speed of maturity of the different storage variants (NMC, LTO, etc.) with gains in terms of autonomy and lifespan. French secondary rail networks are currently poorly electrified (around 15% of the length). However, partial electrification, associated with a dual-mode battery-powered train solution, can reduce investment costs by up to 70% compared to total electrification [1], it is therefore a relevant solution for the decarbonization of secondary rail network.

The hydrogen family is composed of power conversion and storage systems. For electric traction, the power conversion is carried out by a fuel cell. Hydrogen is stored in gaseous (350 or 700 bars) or liquid form. A secondary storage system is added to compensate for the low dynamic reactivity and non-reversibility of fuel cells.

Because they significantly reduce polluting emissions from well to wheel and because they improve the energy balance [2, 3], the solutions retained for future light trains are therefore:

- A dual mode with batteries train capable of using the catenary for traction and/or the recharge of batteries.
- A single-mode H2 hybrid train, composed of H2 tanks, a FC system and traction batteries. This train version is not dual-mode and is not capable of capturing current from the catenary.

The following sections focus on defining the areas of relevance of these two solutions for the entire French secondary rail network according to the electrical infrastructure and the current transport plan and considering energy and power requirements.

3 Methodology

3.1 Dedicated Developed Software Presentation

The proposed approach consists in developing a dedicated simulation tool called QUALESI ("*QUALification de l'Exploitation de Solutions Innovantes*"), interfaced with the SNCF company's information system and playing simulations of dual-mode battery and hydrogen hybrid light trains on the current French railway network [4]. The methodology is as follow:

Precisely describe the railway network in terms of gradient, radius of curvature or even line electrification by using railway infrastructure data. In addition, it is also necessary to collect data describing the transport plan to be able to simulate real missions. Daily transport data are used to describe trains itineraries and time schedules. Every day, more than 10,000 passenger trains run in France.

Model a Vertex-Edge model of the railway network and the train operations, considering the specific features of dual-mode battery and hydrogen hybrid light trains by developing a versatile energetic model. Quasi-static models of the energy storage and generation system have been adopted [5]. It enables high accuracy with less computational time. Used mathematical models are presented in detail in [4].

Visualize the simulations results and performance indicators through cartographic representations of the French railway network.

3.2 Key Performance Indicators

The rail transport plan considers all the provisions necessary for maintaining train timetables and the distribution of the staff in the form of full operating days. These days also include the various operations to be carried out at the station or in the technical center such as preparing and examining the train, refueling, toilet emptying, etc. Thus, the different stages of the train days are opportunities for recharging (recharging batteries or fuel) or energy consumption.

This paper therefore considers entire operation days and not specific typical missions for energetic KPI.

For the dual-mode battery train version, an operating day is qualified as feasible if its battery does not discharge completely (example in Fig. 1 (a)). The corresponding railway lines are drawn in green in Fig. 2.

The energy-relevant lines for operating the H2 hybrid train version are those that the battery train version is not able to cover. These lines can however be identified as "difficult" in terms of timetable keeping due to hybridization and power requirements (see Fig. 1 (b) and (c)) [4]. Difficult hybrid H2 lines are plot in red in Fig. 2.

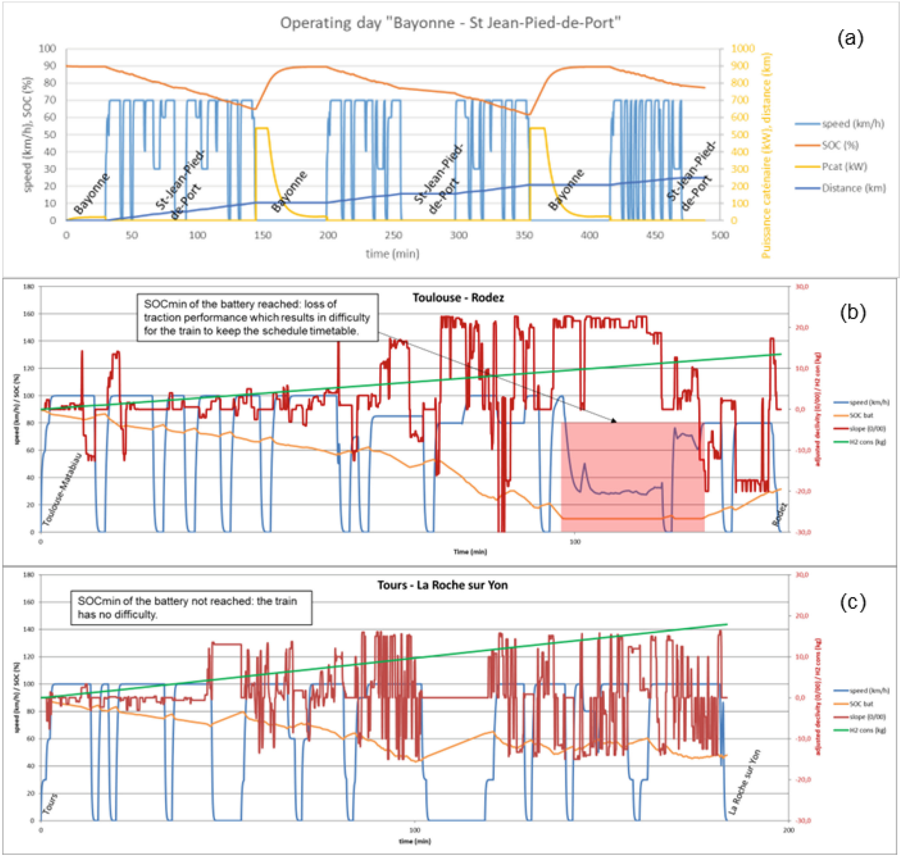

Fig. 1. Examples of all-out speed profile and battery state of charge evolution for (a) a dual mode battery light train version (represents one of the thousand simulations), and (b, c) a hybrid hydrogen light train version

4 Relevance of Dual-Mode Battery and H2 Hybrid Light Train Versions

The studied trains are light regional dual-mode batteries and hybrid H2 trains. Their characteristics are presented in Table 1. These characteristics are assumptions taken in a preliminary phase of the TLi project. 1044 commercial light passenger train daily missions have been simulated. 17 h were necessary to simulate two times (one per configuration) the 1044 missions (30s per simulation).

Table 1. Main parameters of the studied light trains (assumptions)

Parameter	Dual mode batteries	Single mode hybrid H2
Masse	35217 kg	33717 kg
Battery capacity	703 kWh	150 kWh
H2 tank capacity	-	100 kgH2
FC Power	-	100 kW
Maximal speed	100 km/h	100 km/h

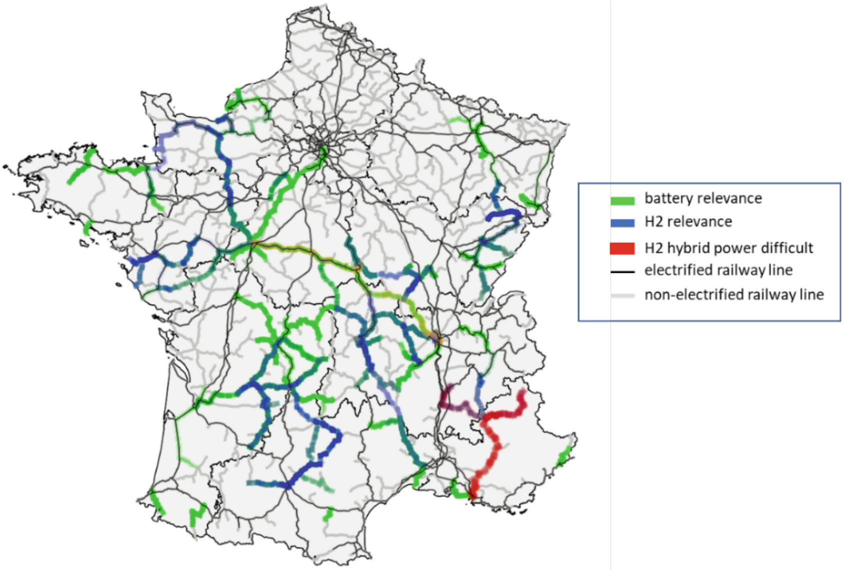

Fig. 2. Relevance of dual-mode battery and H2 hybrid light trains for the French secondary rail network (image produced using QGIS, an open source software).

Based on thousand simulation analysis, Fig. 2 shows the areas of relevance for the dual-mode battery and H2 hybrid versions for secondary rail network:

The relevant lines for the operation of dual-mode battery train version are shown in green. They reflect the feasibility of their operations considering an autonomy of 200 km. To improve these areas of relevance, it is possible to imagine an evolution in battery performance or the implementation of dedicated partial electrification.

Lines relevant for the operation of H2 hybrid light trains are shown in blue. On these lines, the previous battery train versions are not able to cover the current transport plan due to autonomy limitation. This result is valid without subsequent investment in electrification. To fulfill 100% of the transportation plan, H2 version requires 1000 km of autonomy, considering to setting up around twenty H2 distribution stations. However, battery/FC hybridization sizing can lead to traction difficulties having an impact on the train's ability to respect the timetable [4]. Lines described as "difficult" are lines with hilly or mountainous profiles and lines where the speed is continuously maximum for a long period. One solution could be to review the timetable or to envision an advancement in battery and FC performance.

5 Conclusion

There is no one-size-fits-all solution to decarbonize rail transport. Both battery and hydrogen technologies have their own relevance field depending on the technological solutions, infrastructure, and desired transport service.

A dedicated tool, called QUALESI, based on big data, mathematical modelling and geographic information system is used to map and define energetic and power relevance of potential future dual-mode battery and H2 hybrid light trains for secondary rail network. For SNCF, these results make it possible to anticipate infrastructure developpement (partial electrification and H2 stations) and to advise the mobility organizing authorities. It will also profit partners to design the traction systems by energy, power, and functional specifications in the next steps of the TLi train development.

The proposed analysis, however, has limitations. The first is that QUALESI is based on current operations whereas we can expect different future operations and higher service frequencies. The second is that the infrastructure that will be put in place will impact the results. An evolution of our study could be to compare the system costs/benefits of partial electrification versus the installation of H2 fueling stations.

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Development of Next Generation Sustainable Electric Traction Motors

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Abstract. The development of traction motors with easily recyclable rare-earth permanent magnets (PMs) is studied. The primary objective is to find means and technologies that enable the reuse of the PMs without extracting their elements. Both the motor design and PM assembly need to be aligned with this target. Especially, we are focusing on metallic encapsulation of the PMs to make them strong enough to tolerate the disassembly forces. First, we discuss the design, addressing the positioning of the encapsulated PMs to balance between the mechanical and

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electromagnetic requirements. Second, we present the first results on the encapsulation of the PMs for intact disassembly, elaborating on the materials, manufacturing via direct energy deposition, and visual inspection of the results. We aim to contribute to the emergence of the next generation less rare-earth-element-dependent, compact, and energy-efficient electric traction motors.

Keywords: Experimental analysis · mass market motors · numerical optimization · permanent magnets · recyclability

1 Introduction

Present-day electric traction motors rely heavily on the use of rare-earth permanent magnets (PMs) that contain scarce elements like Neodymium and Dysprosium. This dependency is understandable from the perspective of energy efficiency and torque density, but it also introduces several challenges. First, these materials are imported into the EU and are costly. Second, there is a real risk of supply shortage due to the increasing demand that originates from the electrification of different sectors.

In response to these challenges, we are developing next generation traction motors for electric cars and vans in the Horizon Europe project "Design, manufacturing, and validation of ecocycle electric traction motor" (VOLTCAR) project[1]. Our goal is to create a compact, 7 kW/kg and 23 kW/l, energy-efficient, and cost-effective solution. We are using PM-assisted moderately high-speed synchronous reluctance motor technology to reduce the dependence on rare-earth PM materials while simultaneously enhancing their recyclability. The solution must meet the automotive industry's expectations regarding costs, reliability, and integrability, including a digital twin of the motor. We will be extensively testing the 50- and 120-kW traction motor prototypes in a hardware-in-the-loop environment to showcase the benefits of our approach.

Our first considerations and results on the development of the traction motors with more easily recyclable PMs are reported here. Our aim to disassemble the PMs intact and reuse them as such is considered from the early design phases for instance in terms of the number and positioning of the PMs in the motor. Naturally, the best possible solution between performance and recyclability must be sought. Furthermore, as sintered PMs are brittle, they must be mechanically protected so that they can be disassembled intact. Besides the initial designs of motors for recyclability, the first experimentations on the magnet encapsulations will be presented.

2 Methods

2.1 Design Process

Enabling the removal of the PMs intact and their reuse as such, without resorting to indirect methods that involve extracting individual rare-earth elements through chemical processes, is an integral part of our earliest ideation and design phases. First, we propose

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a rotor construction that is composed of three sections with a synchronous reluctance rotor in the middle and PM rotor sections at the ends. The PM material is concentrated at the ends to facilitate easier removal. Additionally, the PMs are encapsulated to improve their corrosion resistance, structural strength, and to ensure their intact removal for a second lifetime.

After the initial parameters of the motor design have been found [1] the electromagnetic, mechanical, and thermal characteristics are optimized through numerical finite element analyses in distinct domains [2]. The optimization process also entails freezing the materials and suppliers for copper wires, PMs, electrical steel sheets, shafts, bearings, supporting structures, and adhesives as individual components and as assemblies that form the stator, rotor, and housing and validating the performance of these assemblies and the complete motor. In this work, we analyze the impact of the encapsulation of the PMs on the electromagnetic torque. The electromagnetic field problem is governed by the Maxwell's equations expressed with magnetic vector potential $\boldsymbol{A}$ as:

$$\nabla \times \frac{1}{\mu}(\nabla \times \boldsymbol{A}) = -\sigma \frac{\partial \boldsymbol{A}}{\partial t} + \boldsymbol{J}_{\mathrm{e}}, \tag{1}$$

in which, the magnetic flux density, $\boldsymbol{B}$, is defined as $\boldsymbol{B} = \nabla \times \boldsymbol{A}$, μ is the permeability of the material, σ the electrical conductivity of the material, t time, and $\boldsymbol{J}_{\mathrm{e}}$ the external current density. The electromagnetic torque can be solved based on Arkkio's method.

2.2 Technique for the Encapsulation of the Permanent Magnets

The first encapsulations of the PMs have been done via direct energy deposition (DED). DED is an additive manufacturing method that is based on the melting of powder with a laser thus creating a solid piece. In DED, the powder is injected directly from the printing nozzle to the melt pool, depositing material layer by layer. This method allows the use of multiple powders during the printing and therefore enables the creation of multi-material components.

3 Results

The targeted key characteristics of the VOLTCAR PM-assisted synchronous reluctance motor (PMaSynRM) and the key characteristics of an automotive benchmark motor are summarized in Table 1. The tabulated values reflect the key objectives of the VOLTCAR traction motor developments; the motor should be fit for electric vehicle mass-market application, compact with high-power density and high-specific power, and nearly free of rare-earth PM material. Key means for reaching the set targets are increasing the speed and voltage of the motor from the present state-of-the-art levels, as shown in Table 1. The first steps towards these set targets are presented in the following sections.

3.1 Effect of the Permanent Magnet Encapsulation on the Motor Torque

The initial design of the motor's PM rotor segment without the encapsulations is shown in Fig. 1, left. Materials for the encapsulation and the resulting motor designs were

Table 1. Properties of an automotive benchmark motor and targets for the VOLTCAR motor.

Parameters	Benchmark Motor	VOLTCAR Motor
Motor type	Radial flux PMSM	Radial flux PMaSynRM
Speed rated/max (rpm)	5 000/18 000	10 000–12 000/20 000–24 000
DC voltage peak (V)	400	800
Power continuous/peak (kW)	130/220	120/210
Rare earth PM material (kg)	1.8	<0.3
Est. power density (kW/l)	16.5	>23
Est. specific power (kW/kg)	3.2	>7

developed by balancing between the mechanical and electromagnetic requirements. To minimize the disruption of the magnetic flux through the PMs, we propose using magnetic materials, such as pure iron, on the sides of the magnets where the magnetic flux passes vertically (dark gray in Fig. 1, middle). Instead, the sides of the magnets parallel to the magnetic flux (black in Fig. 1, middle) must be encapsulated with non-magnetic materials like Inconel, to prevent the circulation of flux on these sides. Figure 1, right, compares the magnetic properties of the stator and rotor ferromagnetic electrical steel sheet material with the pure iron used for the encapsulation.

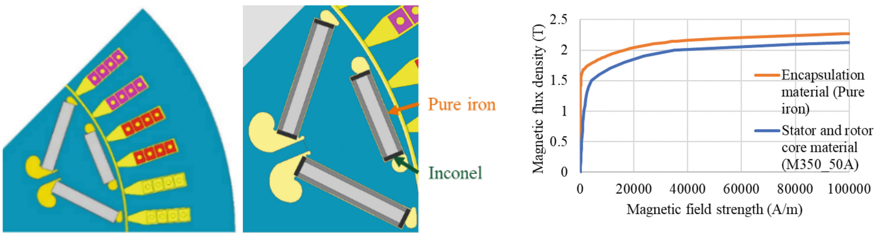

Fig. 1. Geometry of one pole of the initial motor design, PMs shown with a light gray color (left). An example of magnet encapsulation (middle). Magnetic properties of the stator and rotor cores and encapsulation magnetic material (right).

Accommodation of the PM encapsulations requires small changes in the original design, (Fig. 1, left). Based on the mechanical analysis of the initial rotor design, it was recommended to maintain the thickness of tangential and radial ribs at approximately 1 mm and 1.5 mm, respectively. This is to prevent high stresses in those areas and ensure mechanical stability. Additionally, to preserve the electromagnetic performance of the motor, it is essential to minimize changes to the magnet sizes and the flux paths in the rotor. For reference, the magnetic flux density of the motor model without any encapsulation at the rated current is presented in Fig. 2.

To meet the requirements when adding the encapsulations, we shifted all PMs toward the rotor's center by the thickness of the encapsulations. Figure 3 presents the geometry of three models with varying encapsulation thicknesses: 0.15 mm, 0.3 mm, and 0.5 mm.

It should be noted that the size of the magnets remained unchanged, except for the length of the V-shaped magnets, which was slightly reduced to maintain the thicknesses of the surrounding ribs.

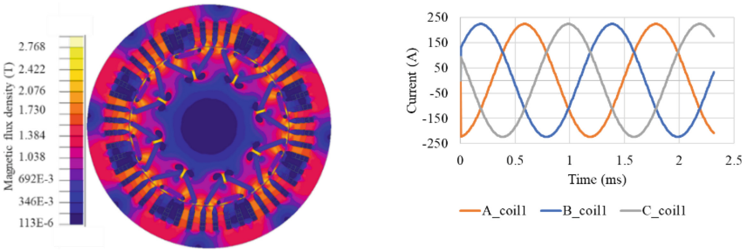

Fig. 2. Magnetic flux density of the motor's PM motor segment (left) at rated current (right). Source: Authors.

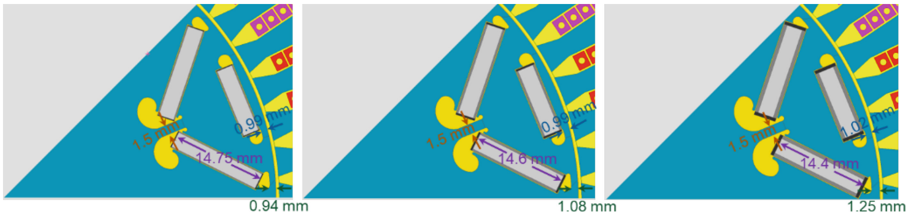

Fig. 3. Designs with 0.15 mm (left), 0.3 mm (middle), and 0.5 mm (right) thick encapsulations.

Figure 4 compares the electromagnetic torque of the model without encapsulation with that of the models with encapsulations. As the encapsulation thickness increases, the average torque decreases slightly, while the torque ripple (as the difference between the maximum and minimum torques over average torque) increases.

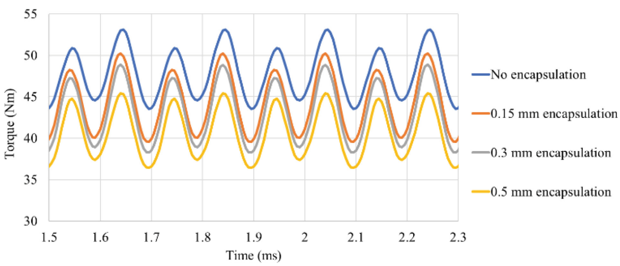

Fig. 4. Torque without and with PM encapsulation. No encapsulation: average torque 47.9 Nm, torque ripple 20%; with 0.15 mm encapsulation thickness; average torque 44.4 Nm, torque ripple 24%; average torque 43.0 Nm, torque ripple 25%; average torque 40.6 Nm, torque ripple 22%.

3.2 First Permanent Magnet Encapsulation Tests

The first encapsulation tests were carried out on cylindrical PMs with a diameter of 4.8 mm and height of 1.8 mm. Magnets of these shapes are not directly applicable to the example motor designs shown in Fig. 3, but to begin with, we wanted to assess which manufacturing technologies could be applicable for creating strong enough support without deteriorating the magnet characteristics.

The encapsulations were created using a commercial multi-material DED machine (MX-Lab, Insstek Co., Republic of Korea). The bottom layer of iron powder was first printed on the top of the DED printing platform. The ring section surrounding the PMs was then printed from Inconel 718 on the top of the bottom layer. After the insertion of the PM into the encapsulation, the top layer of iron powder was printed on top of the PM and the upper surface of the ring section. The bottom and top layers were approximately 0.3 mm thick. For the ring section, different outer diameters were explored. In the manufacturing of the top layer, different laser powers 180 W, 200 W, and 220 W were used. Based on the visual inspections of the encapsulated PMs, it was found that with lower laser power, the magnets remain intact while with higher powers, the magnets tend to crack as can be seen in Fig. 5. Further, it was also observed that the smaller the outer diameter of the ring section is, the more prone the PMs are to crack.

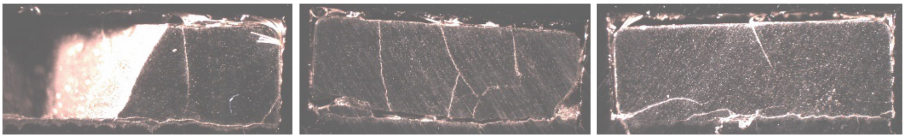

Fig. 5. Image of PM cross-section from the side for top layer printing powers 220 W (left), 200 W (middle), 180 W (right). Source: Authors.

4 Discussion and Conclusions

The design considerations of electric traction motors with more easily reusable PMs were discussed. We assume that the PMs are too brittle to be removed intact without an encapsulation. According to our initial results, the encapsulation of the PMs has a clear impact on the motor's average torque and the torque ripple. However, this impact might be tolerable if the encapsulation facilitates the dismantling and reuse of the magnets.

The present study features the preliminary outcomes of the manufacturing process of PM encapsulations. The investigation reveals that with the aid of DED technique, coupled with the selection of optimal printing power and thickness, the PMs can be encapsulated without any damage. The next phase of this research aims to ascertain whether the encapsulated PMs can offer the same level of performance as their non-encapsulated counterparts through re-magnetization.

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Strategic Allocation of Research Funding: A Network Analysis Approach with a Focus on Batteries for Road Transport - A Case Study

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Abstract. This study builds upon a previous work [1] extending the analysis of the properties of the networks constructed by Horizon 2020 funded projects and in the UK for one specific research area, batteries for electric vehicles, in order to gain further insight into what impact funding can have in achieving the goals of the EU. Social Network Analysis is used to determine the network properties. The results show the impact of funding compared to the previous analysis on creating structure in the area of batteries that was associated with a thinly spread network of primarily research organizations. An investigation of the direct impact of funding found that similar structuring of the network could be achieved with similarly significant investments exemplary in the UK. Moreover, in both national and EU example cases a few partners stand out and may be playing an important role in connecting partners and projects. In an additional step it was attempted to show that it is possible to create a structure of theoretical structure (based on the existing collection of projects) via extending one variable; this gives valuable insight into where future funds or individual project structures could have the strongest impact on achieving an idealized reference structure.

Keywords: Social Network Analysis · Battery Technologies · Innovation Ecosystems · Research Policy

1 Introduction

Social network analysis (SNA) tools are widely used to analyse collaborative research projects in order to assess the effectiveness of innovation systems such as the network of relationships between partners that result from cooperation in funded projects [3–6]. By developing research consortia, partners and projects are linked to form networks that can be considered as proxies of the respective innovation systems. SNA is used to examine the main topological features of these networks.

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Using this approach, in [1, 2] we analysed the properties of the networks that emerged from Horizon2020 funded projects in four research areas, internal combustion engines (ICE) for hybrids, batteries for electric vehicles, advanced functional materials, and automotive power electronics. SNA was used to determine the network properties and centrality measures of the nodes to identify the most important actors. The analysis was complemented with publication and patent data to investigate if participation in Horizon2020 projects influences research and innovation performance. The results indicated that projects are formed by the same core of key partners, located in or around the main centres of automotive manufacturing in Europe.

In this paper, we expand our previous work with a dive in one area to gain further insight into what impact increased and/or targeted funding can have in achieving the EU goals. The work focuses on battery technologies, an area of particular importance since know-how for battery development and production is vital for the future success of electrification in Europe and attaining sovereignty in this area. A huge effort is needed to attain this goal in comparison to the area of ICE where technology leadership has been achieved "organically" and over a much longer period of time. In this paper we provide evidence on two aspects:

- First, we compare the size and the structure of the innovation ecosystems in the field of battery technologies both in the EU and the UK, and their coupling;
- Second, we assess how different is the network structure of EU funded research in battery technologies (where Europe seeks technology leadership) and ICE (where Europe is technology leader). We also attempt to answer how research could be funded in the EU so that the network of batteries converge to the one of ICEs.

2 Methods

SNA is first used to examine the main topological features of the networks that have emerged from collaborative research projects, i.e., network density, diameter and size as well as the clustering coefficient. *Network density* is measured as the ratio between the actual number of edges and the number of possible edges. Thus, values close to 1 correspond to very dense networks. *Network diameter* is defined as the maximum length of all geodesic distances (i.e., indicates the farthest path). The *size of the network* is defined as the number of nodes in the network. The *clustering coefficient (*or transitivity) is defined as the number of transitive triples divided by the number of potential transitive triples. If its value is near 1, the partners of any node have a high probability of being partners with each other.

Then, following the approach in [3], a set of four positional indicators of the nodes in the network is derived. *Degree centrality* is an indicator of the strength of links between a participant and all the other network participants. A high value of degree centrality suggests that the participant is connected to a large number of actors in the network and thus has access to more information. *Closeness centrality* measures the distance of each node from all others, being an index of the viability of access to information possessed by the node, since a higher distance amongst nodes implies weaker links and thus reduced information flows. *Eigenvector centrality* is an indication of the proximity of a node to the core of the network, which is essentially the most active, well-connected and important actors. *Betweenness centrality* is a measure of the extent to which a node acts as a connector of other nodes, i.e., nodes with a high betweenness centrality connect different groups. Thus, when the betweenness centrality is high, the node has access to different and new flows of information through partners who have participated in mutually unconnected projects.

Simulations were also conducted to create synthetic project partnerships via modification of existing networks to improve network characteristics. We focused on density and eigenvector centrality, matching those of our reference networks.

The data used in the analysis were acquired from the EU open data portal [7] and the UKRI Gateway to Research portal [8]. Data acquisition, analysis and mapping were performed using R [9], while Gephi [10] was used for network visualisation.

3 Results and Discussion

3.1 Comparison of the Battery Technology Ecosystems in EU and the UK

The extended analysis of EU-funded projects in the field of battery technology for road transport has considered 88 projects, in comparison to the 27 projects analysed in [1], that started between 2015 and 2023, with €634.67million EU contribution. These projects constitute a network (see Fig. 1 (a)) of 764 participants (of which 504 private companies, 113 higher education institutes, 81 research organisations and 24 public sector organisations) from 43 countries. The number of edges in this network is 1985, its diameter is 5, and its density was calculated to be 0.04. There is only a single cluster present in this network and the average clustering coefficient is 0.861. The network centrality rankings show that ten most active actors occupy the top 10 positions in three measures of centrality (degree, closeness and eigenvector).

Regarding project participations, the ten most active actors are found to be Fraunhofer, CEA, Centro Ricerche FIAT, Austrian Institute of Technology, CIDETEC, AVL List, Avesta Battery & Energy Engineering, Vrije Universitet Brussel, RWTH Aachen, CIC EnegiGUNE and Virtual Vehicle Research. The map in Fig. 1(b) shows that the majority of the participants are located in a box defined by Northern Spain, Paris, Wolfsburg, Berlin, Graz and Torino, and this correlates well with the values of the EC contribution per country: Germany, France, Spain, Belgium, Italy and Austria have been awarded 73.2% of the EC contribution.

We have also considered the national example of 118 UK funded collaborative research projects in the field of battery technology, supported by InnovateUK, that started between 2015 and 2023, having a total government contribution of £578.97million. These constitute a network of 424 participants (347 private companies, 41 higher education institutes, 7 research organisations and 20 public sector organisations) from 4 countries, shown in Fig. 1(c). The network has 1745 edges, a diameter of 7, and a density of 0.019. There average clustering coefficient was found to be 0.897.

From the map in Fig. 1(d) it is evident that the majority of the participants are located in two major areas, in and around London and in a triangle defined by Birmingham, Leicester and Stratford-Upon-Avon, which includes Coventry and Warwick. Regarding project participations, the ten most active actors are found to be University of Warwick, Delta Cosworth, Jaguar Land Rover, Imperial College, BMW Motorsport, Williams

Advanced Engineering, AMTE Power, University College London, Coventry University and AGM Batteries. Moreover, the City Council of Coventry was awarded a single project named UK Battery Industrialisation Centre with a grant of £114.5 million with the participation of the Coventry and Warwickshire Local Enterprise Partnership and WMG, at the University of Warwick.

By the nature of the funding instrument, Innovate UK, there is a strong involvement of industrial partners. Beyond the central role of Universities in the UK, instead of Research Centres in the EU, the main qualitative difference between the EU and the Innovate UK datasets are the active role of some public organisations (such as City Councils or equivalent) in the projects examined. This means that the policy instruments put in place through Innovate UK are actively seeking the participation of such organisations in collaboration with research and enterprise, with the purpose of providing testbeds for deploying or demonstrating innovative solutions.

We have identified 29 actors that participate in both EU and UK ecosystems. However, the degree of participation in terms of number of projects and the amount of funding is considerably unbalanced. University of Warwick is the most prominent example, since it participates in 38 InnovateUK projects with a total grant of £26.5million and in a single EU project with €0.48million of EU contribution in the same time period.

3.2 Network Synthesis

Our key objective for this part was to improve the network's density and eigenvector centrality that was obtained by analysing 27 projects in the field of batteries for xEVs in [1, 2], so that they converge to the respective value of network density and the distribution of eigenvector centrality of what we consider as the reference network obtained originally by analysing 20 projects on ICEs, also reported in [1, 2]. The eigenvector centrality distribution showed that the battery research projects involved numerous industrial partners (nearly the same number as the ICE-HEV), but the top 20 positions in the ranking based on eigenvector centrality were dominated by research partners. Moreover, many industrial partners were participating in only one project, which was confirmed by a very low eigenvector centrality. In order to achieve a higher network density in the synthesized network, industries low in eigenvector centrality were strategically added to projects that had a low representation of industrial partners. 15 partners, rather renowned industries, were added to at least five projects, and taking care that partners do not participate more than once in a particular funding call.

In this way, our experiments have shown that the network density of the synthesized network could be significantly increased by 50% from the original 0.092 to 0.14, only missing the reference network density of 0.19 by 30%. Moreover, this manual injection of 15 industrial partners to at least five projects increased the overall participant occurrences by 23%. And this could be achieved with only slightly more than 1% increase in overall EU funding based on the assumption that that the budgets of each new partner averaged €150 000 per occurrence. Overall, the resulting network showed similar distinct structure that is observed with the reference target network structure.

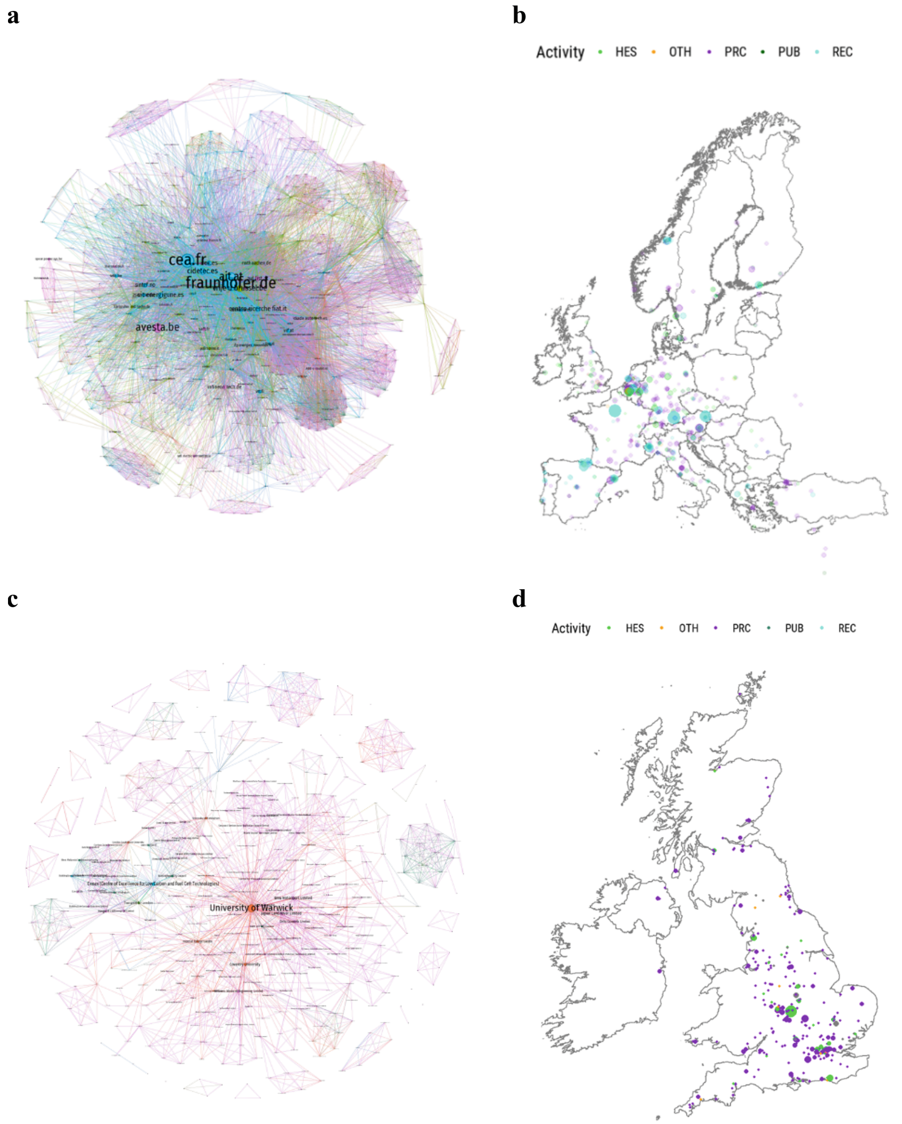

Fig. 1. (a) Network of the European research and innovation ecosystem for battery technology. (b) The territorial dimension of the EU ecosystem. (c) Network of the UK research and innovation ecosystem. (d) The territorial dimension of the UK ecosystem.

4 Summary and Outlook

It is postulated that strong research and innovation ecosystems are essential for achieving technology leadership, fundamental for securing, maintaining and improving European competitiveness. These ecosystems are especially vital for tackling fields of high innovation demand that require both a better fundamental understanding of the physics and a substantial improvement in active and passive materials. It is also essential to increase the involvement of industrial partners to secure the pathway to exploitation.

The identification and analysis of such ecosystems strongly depends on the availability of data that can be used as proxies to actor interactions. Our comparative analysis of the EU and the UK ecosystems for battery technologies has shown that using national funding through appropriate policy instruments can lead to strong territorial ecosystems that act in parallel to the pan European ones. These can be linked by ensuring that key stakeholders, identified by high eigenvector centrality, are participating in both networks. The greatest benefit that the approach and methodology offer at the moment is give the funding agencies the ability to assess ex-post the impact that funding has on creating the desired networks of excellence. Furthermore, the success of creating a synthesized network with the desired results demonstrates the capability the approach has to generate ideal networks with variables relevant for funding agencies so that ex-ante analysis is possible and can be used in testing strategic future funding schemes.

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A Cost Modeling Framework for Modular Battery Energy Storage Systems

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Abstract. This paper presents a cost modeling framework for battery systems. Based on findings in battery cost modeling literature, there is a need for scalable, systematic frameworks to model cost. The framework in this paper, which is developed with a systems approach in mind, incorporates parametric cost models that consider scaling in component rating, future cost prediction and economies of scale with a limited set of tunable parameters per component. This framework is employed to construct an instance of a novel battery architecture, the module level converter topology, in a scalable way using different classes for (sub-)systems and indivisible components, based on the desired power output and energy content of the system. By doing so, the system costs of the novel hybrid battery architecture are compared to a baseline battery topology in terms of cost decomposition. The prospects of this novel architecture are also mapped out in terms of production volume and future component costs.

Keywords: Cost modeling framework · Parametric cost model · HESS

1 Introduction

In the transportation sector electrification, modular battery systems and hybrid batteries have been identified as promising strategies to meet the critical requirements on energy, power density, lifetime and safety. Today, multiple promising topologies for battery hybridization can be identified. Missing however are systematic cost modeling approaches that can evaluate the total system capital cost with respect to key requirements such as battery capacity, voltage, and power output.

In the past decades, various cost models on batteries have been proposed. Overall, cost models presented in existing literature, based on their purposes, capture different elements in the battery industry on various fidelity levels. Fabian *et al.* grouped these models into four categories: intuitive models, analogous models, parametric models, and bottom-up models [1]. An intuitive model is largely based on expert insights and therefore requires little input data regarding the elements underlying the batteries [2, 3]. For this reason, these models have little reproducibility and their validity also decreases over time due to technological advancement and the change of macro-economic situations. Analogous models make projections by performing regression analyses on historical data. For instance, Penisa *et al.* [4] and Schneider *et al.* [5] presented analogous models

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to project respectively the battery system costs and battery cell costs evolution in the future. However, due to the limited representation of the internal structure, it is challenging for analogous models to consider the evolution of different cost elements over time and the economy of scales. In order to consider more factors (such as technology advancement, dependency on critical materials, and economy of scales (EoS)), one should leverage a higher fidelity model – the so-called parametric model – where the cost elements are represented by cost functions characterizing the cost evolution as a function of time, size, and production [6–8]. One of the most comprehensive cost model in this spectrum is the BatPaC model developed by Argonne National Laboratory which comprises of a comprehensive battery system decomposition, critical design considerations (e.g., power, energy, voltage, etc.), and other fixed investments costs and overhead costs [9]. Nevertheless, the high fidelity of the model, in combination with it being excel-based, reduce its scalability, transparency, and customizability. Hence, it is limited in performing analysis on the cost components and their evolution. In short, the fundamental difference between a parametric and an analogous model is the use of equations on cost elements level. The most sophisticated cost models – the bottom-up models – add another layer of complexity by modeling the complete manufacturing process sequence. The cost is therefore estimated based on the cost incurred by each step in manufacturing [10–12].

To the best of the authors' knowledge, the cost modeling framework presented in this study is the first scalable, transparent, and modular parametric cost model that allows the user to analyze the cost evolution of selected cost elements against size, production, and technology advancements over time. In this regard, this paper presents a scalable, transparent, and modular battery system cost modeling framework that captures individual components and their dependency relationships and is capable of performing trend analysis of battery size, production upscaling and future cost.

The battery architecture for which the cost model is employed features a scalable module level converter (MLC) topology. Herein, the Hybrid Energy Storage System (HESS) capacity is set by the number of parallel "strings", which features either high power (HP) or high energy (HE) cells. Each string contains "modules" connected in series, which are fully managed battery packs that include a DCDC-converter.

Though this paper is scoped around CAPEX, other factors do affect TCO: MLC boasts efficient converters, minimizing operational cost and standalone modules allow for resale to lower end markets (e.g. stationary) when cell degradation and internal cell resistance have exceeded their acceptance limits, cutting TCO towards EOL.

2 Framework Outline

This section will outline the developed framework, that is set up with a systems-approach in mind, allowing with minimal effort to construct a system-of-systems hierarchy of components at different levels. The object-oriented implementation of the first version is developed in Python.

A separation into classes is considered, to generalize functionality as much as possible. The "System" class objects can own components, "AtomicComponent" cannot (Fig. 1).

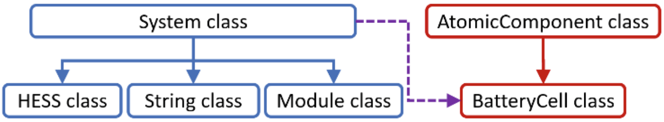

Fig. 1. Class hierarchy within the framework

The attributes and methods of the "System" class can be grouped into 3 themes: managing components, electrical properties and cost modeling functionalities, The "Atomic-Components" class only includes rating and cost modeling attributes. The extended "BatteryCell" class includes the electrical properties as well.

A system is generated based on its requirements and a set of heuristics:

- The bus voltage and hybrid (HE/HP) capacities in ampere hours must be specified.
- The (fixed size) modules are placed in series to obtain the desired bus voltage.
- The ampere hour capacity of a module depends on the degree of downregulation by the DCDC-converter to match the desired bus voltage across all modules.

Whenever a HESS system instance is created, it creates for both HE and HP capacities a number of strings, which in turn allocate modules to the strings. At every system level a number of atomic components are also added (mostly from an Excel file). After this, the system is set up for queries, PBS generation or cost analyses.

3 Cost Modeling

In Sect. 3.1, a single, fixed cost is attributed to each system component along with a cost category. This is extended with cost variability modeling in Sect. 3.2.

3.1 System Cost Construction Per Category

To compute system cost, each component has a cost and category. Given the scalable framework, total (sub-)system cost is easily constructed, as can be seen in Fig. 2.

3.2 Parametric Cost Modeling

The fixed cost approach is extended to three cost dimensions, being:

1. Component scaling, i.e. increased cost due to e.g. higher component power rating
2. Future cost prediction, i.e. potential price declines due to technology resources, etc.
3. Economies of scale: higher discount due to higher production/sales volumes, etc.

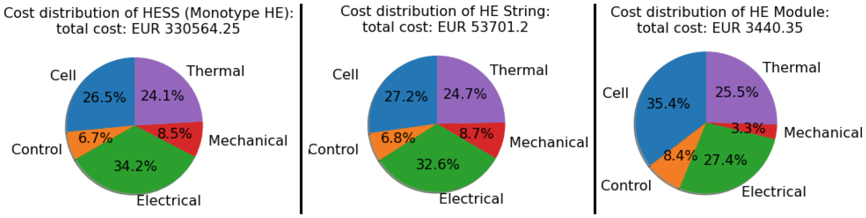

Fig. 2. Cost per category at HESS, string and module level

For each of these a simple parametric model is proposed. The general equation is expressed by Eq. 1. The fixed reference cost, $cost_{ref}$ from Sect. 3.1 represents the cost (1) at a given, normative rating (2) at the present (3) as a single item.

$$cost_{scaled} = cost_{ref} * f_{scaling}(R, f_{cs}) * f_{pred}\left(t_{yr}, \tau_{50}\right) * f_{EoS}(N, c_{eos}, f_{lvd}) \tag{1}$$

Component Scaling Cost Model. The components rating ratio R compared to a reference rating affects its cost by Eq. 2. A rounding function with 6 steps per decade is introduced to mimic the discreteness of product sizes (i.e. E6-scale for capacitors). Secondly, f_{cs} accounts for the price trend which typically introduces a discount for higher rated components (i.e. 10x the rating at only 6x-8x the price).

$$f_{scaling}(R, f_{cs}) = 10^{(1-f_{cs})\frac{ceil(6\log_{10}(R))}{6}} \tag{2}$$

Future Cost Prediction. Since price forecasting has limited accuracy, a simple single-parameter exponential represents the future cost factor is given by Eq. 3:

$$f_{pred}\left(t_{yr}, \tau_{50}\right) = 2^{\frac{-t_{yr}}{\tau_{50}}} \tag{3}$$

where t_{yr} is time in years and τ_{50} is the expected 50% time for each component. A negative τ_{50} can accommodate inflation if needed.

Economies of Scale (EoS) Cost Model. With higher volumes, price per component tends to drop. Sometimes significantly. To match this, a sublinear trend is proposed

$$f_{EoS}(N, c_{eos}, f_{lvd}) = N^{-c_{eos}+c_{eos}e^{-f_{lvd}\sqrt{N}}} \tag{4}$$

The coefficient c_{eos} accounts for high-volume discount, although the discount margin flattens out. Resource scarcity is not modeled. The low volume discount factor f_{lvd} is added to better track low volume price trends. Figure 3 features all three cost trends.

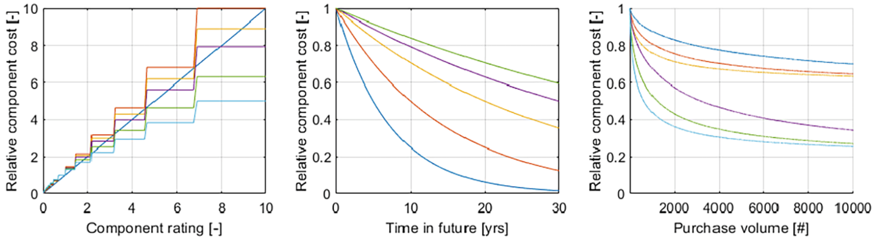

Fig. 3. The three cost functions for different parameter

4 Trend Analysis

First, the MLC topology is compared with a baseline topology (i.e. single battery pack with large DCDC converter). Cost is impacted by differences in component count as well as component ratings. Price comparison in Table 1 reveals that for the current set of cost parameters, the MLC topology still ends up ~30% higher in cost than the baseline design, independent of system size (although upscaling from 1 to 5 MWh saves ~18% due to economy of scales for both topologies). Costly additional CPU's and intermodular connectors disadvantage the MLC topology. However, in contrast with baseline the MLC topology is hybrid-capable (allowing capacity savings).

For a second case, the cost for a 1 MWh HESS is projected into the future, also potential production upscaling is considered. Figure 4 show the price prediction depending on volume for purchase now and in 10 years. Cost categories reveal lithium cells will continue to become cheaper over time and with production upscaling, which may affect cost composition of battery packs, as lithium may no longer dominate.

Table 1. System costs in euros, with relative comparison to 1 MWh Baseline

Cost category	1 MWh Baseline	1 MWh MLC	5 MWh Baseline	5 MWh MLC
Total cost	259k (100%)	331k (+27%)	1069k (−18%)	1423k (+10%)
Cells	88k (100%)	88k (+0%)	380k (−13%)	380k (−13%)
Control	1k (100%)	22k (+2121%)	2.6k (−47%)	95k (+1804%)
Electrical	72k (100%)	113k (+58%)	260k (−27%)	482k (+35%)
Mechanical	29k (100%)	28k (−3%)	123k (−15%)	122k (−16%)
Thermal	70k (100%)	80k (+13%)	303k (−14%)	345k (−2%)

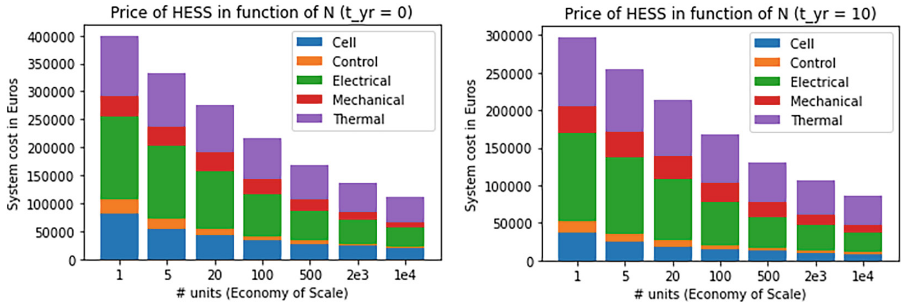

Fig. 4. System cost depending on production volume in present (left) and 10 years (right)

5 Conclusion

A scalable, parametric cost modeling framework has been presented, which was applied to hybrid batteries for vessel applications. This allowed assessment of future viability of modular battery topologies at sea. Further development paths may include further generalization of the framework to arbitrary battery architectures and detailing of data-based cost parameters to improve the predictive power of the framework.

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Structural Batteries for Aeronautic Applications

The Promise of Zero Weight Penalty Energy Storage

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Abstract. Electrification of aircraft propulsion is one key enabler to cut emissions from aviation and meeting the EU Green Deal target of carbon neutral air travel by 2050. While batteries enable highest energy efficiency, their rather low energy density will remain the bottle neck, even with maturing Li-ion technology. Multifunctional electrical energy storage, equivalently referred to as structural batteries capable of storing electrical energy while bearing mechanical loads, could overcome this energy density limit of conventional, monofunctional batteries, as they offer integration of energy storage at near-to-zero weight penalty. So far none of the many structural battery concepts investigated over the last decades has shown multifunctional efficiency adequate for aeronautic applications, and several gaps in research, technology development and in airworthiness certification have never been tackled.

This paper presents the progress in two EU-funded research projects, SOLIFLY and MATISSE, targeting structural battery technology for aerospace applications and its potential for aircraft electrification. Structural battery electrochemistry based on energy dense active material, and cell and structural integration concepts have been developed and demonstrated, allowing projections that improved technology could double the effective system-level energy density of monofunctional batteries, significantly reducing the battery weight penalty, the main barrier to the introduction of batteries for larger aircraft.

Keywords: Aircraft electrification · Reduction of GHG emissions · Multifunctional electrical energy storage · Structural batteries

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List of Acronyms

BCE	Bicontinuous electrolyte
CF(RP)	Carbon fibre (reinforced polymer)
EVTOL	Electric vertical take-off and landing
(G/V)ED	(Gravi-/volumetric) energy density
LFP	Lithium Iron Phosphate
NMC	Lithium Nickel Magnesium Cobalt Oxide
SB	Structural battery
UD	Unidirectional

1 Introduction

Electrification of aircraft propulsion is one key enabler to cut emissions from aviation and meeting the EU Green Deal target of carbon neutral air travel 2050 [1]. This requires a paradigmatic change of the energy carrier and its storage onboard the aircraft. Lithium-ion battery technologies are developing towards higher energy densities, enabling first type-certified battery-electric light aircraft. However, the theoretical limits of this battery technology are expected to be reached in the coming years, while post-Li-ion batteries (e.g. metal-S or metal-O_2) are still far from market [2, 3]. This poses significant challenges for electrifying the propulsion of larger aircraft [4]. Solid-state battery technologies show highest potential for future hybrid-electric (commuters with up to 19 pax and regional aircraft with 50–70 pax) and all-electric propulsion (EVTOL), see Table 1. However, integrating conventional, monofunctional battery cells into modules/packs/systems comes with substantial weight penalty, currently typically around 1.3–1.4. Even when significantly improved, packaging efficiency of monofunctional batteries will always remain below 100% and battery weight will remain a limiting factor for electrifying large aircraft propulsion.

Table 1. Battery generations fit for future air transport applications (adapted from [5])

Generation	Battery electrochemistry [Cathode | Electrolyte | Anode]	Expected cell GED [Wh/kg]	Current TRL	Fitness for air transport applications (entry into service 2035)
3a	NMC622, NMC811 | organic | C + Si (5–10 wt%)	350 to 400	8–9	minor applications → non-propulsive systems → small aircraft propulsion
3b	HE-NMC, Li-rich NMC, LNMO | organic | Si/C		5–6	

(*continued*)

Table 1. (*continued*)

Generation	Battery electrochemistry [Cathode ǀ Electrolyte ǀ Anode]	Expected cell GED [Wh/kg]	Current TRL	Fitness for air transport applications (entry into service 2035)
4a	NMC ǀ solid electrolyte ǀ Si/C	400 to 500 +	3–4	non-propulsive systems → hybrid/all-electric propulsion
4b + c	(HE-)NMC ǀ solid el. ǀ Li-metal		2–3	
5	beyond Li-ion: Li-O_2, Li-S	500 +	1–2	long term solution for hybrid/all-electric propulsion

Multifunctional electrical energy storage, equivalently referred to as *structural batteries (SB)*, are capable of storing electrical energy while bearing mechanical loads, promising seamless integration at near-to-zero weight penalty. Simplest is to integrate conventional lithium-ion batteries into (composite) structures where the cell casing contributes to the load bearing of the overall structure, whereas the other cell components remain monofunctional only contributing to energy storage. However, this approach, currently established in automotive industry and under development for aeronautic applications, promises only limited benefits, up to +16% in range for automotive. In current research the dominating approach for increasing degree of multifunctionality of SBs is *functionalization of structural composites* to achieve energy storing capabilities, typically using CF directly as anode material (similar to graphite in a conventional battery) but coating them with an active material for the cathode side and exchanging the CFRP thermoset matrix with a BCE to ionically connect anode and cathode side. Although this cell design is considered as very promising regarding its mechanical properties, so far only low electrochemical performance could be achieved (less than 15% GED of conventional cells [6]) and many challenges are still to be overcome, including adhesion of the active material on CF, development of a suitable BCE, and processability limitations, currently only possible within a glovebox. The approach followed in this research of *mechanically reinforcing the cell components* seems more promising for aeronautic SB as they will compete foremost with high energy monofunctional Li-ion batteries with double the energy density as today, while CFRP structures are already highly matured [7].

2 Airworthy Structural Batteries

The EU-funded research projects SOLIFLY and MATISSE target SB technology for aerospace, combining research and technology development in the fields of (a) structural electrochemistry with state-of-art high-energy active materials that is performant, safe, mechanically capable and thermally stable; (b) integration of SB cells into CFRP laminate and sandwich composite structures, considering structural materials and production techniques accepted by aeronautic industry; (c) on-cell sensing and monitoring micro-electronics; (d) manufacturing and certification while exploring the potential of deploying such technology in multiple aircraft categories. Furthermore, aspects of manufacturability, scalability at aircraft level and airworthiness certification are tackled. Within SOLIFLY and MATISSE, SB has been demonstrated first in a stiffened composite panel, i.e., a standard interior aircraft part, and then in a full-scale detachable wingtip of a full-electric light aircraft to achieve TRL 4 by 2025.

Multidimensional Approach of SB Development in SOLIFLY/MATISSE
SOLIFLY/MATISSE SB development considers a multitude of factors and conditions relevant to aeronautic structural batteries: (a) *Multifunctional* (electrical-mechanical) *performance* of the structural electrochemistry [8] that is based on high-energy NMC cathode active material. (b) *Safety*, aerospace key driver, is addressed by utilizing a non-flammable ionic liquid-thermoplastic polymer electrolyte for safe operation as well as safe handling of SB cells during structural integration as composites are manufactured in (moist) air, not in a glove box or dry room. (c) The SB electrochemistry is *processable* with established battery manufacturing methods and is *scalable* from lab to cell production line. Two SB cell designs are studied in SOLIFLY, a laminate type and one with coating CF, see Figs. 1a-b, to compare the concepts. (d) The *structural integration* of SB cells in high performance aeronautic laminated CFRP structures aims at minimizing the impact of the SB cell on load bearing and weight, and understanding better the damage and failure process [9], Fig. 1c. (e) *Compatibility* between SB and structure is established, as the use of materials and processes that are widely accepted by aerospace industry should facilitate the adoption of SB technology. For instance, the CFRP curing cycle was aligned with high temperature resilient SB materials that in turn are also beneficial for SB safety.

In MATISSE, SB multifunctional performance will be further optimized and the dimensions of multifunctionality will be expanded with integrating a multi-measurand (electrical, thermal, mechanical, EIS) microchip system, constituting a smart SB cell, see Fig. 1d, that enables health monitoring of cell and structure from first charge to end of life. Multiple smart SBs integrated into a structural part could form a distributed sensor network, opening new possibilities for smart aeronautic structures.

SOLIFLY/MATISSE SB technology will be demonstrated on the test bench with a stiffened panel, representing a standard internal part, Fig. 1e, and extending the structural integration concept further to sandwich components, in a newly designed detachable wing tip of a full-electric light aircraft able to supply to some part electric energy for propulsion, Fig. 1f.

3 SB KPIs and Potential

Integrating SB in solid composite structures, the amount of electric energy stored per volume (VED, Wh/l) and per added weight (ΔGED, Wh/Δkg) is of interest. Table 2 gives the current status of the energy storage capabilities of SOLIFLY SB and projects its evolution, based on actual measurements (while improving also their structural capabilities to become adequate for the specific application cases). While the technology already outperforms other work (e.g. [6] achieving 41 Wh/kg), complex electrochemical interactions inhibit to harvest its full potential. Once this is overcome, the SB can be further

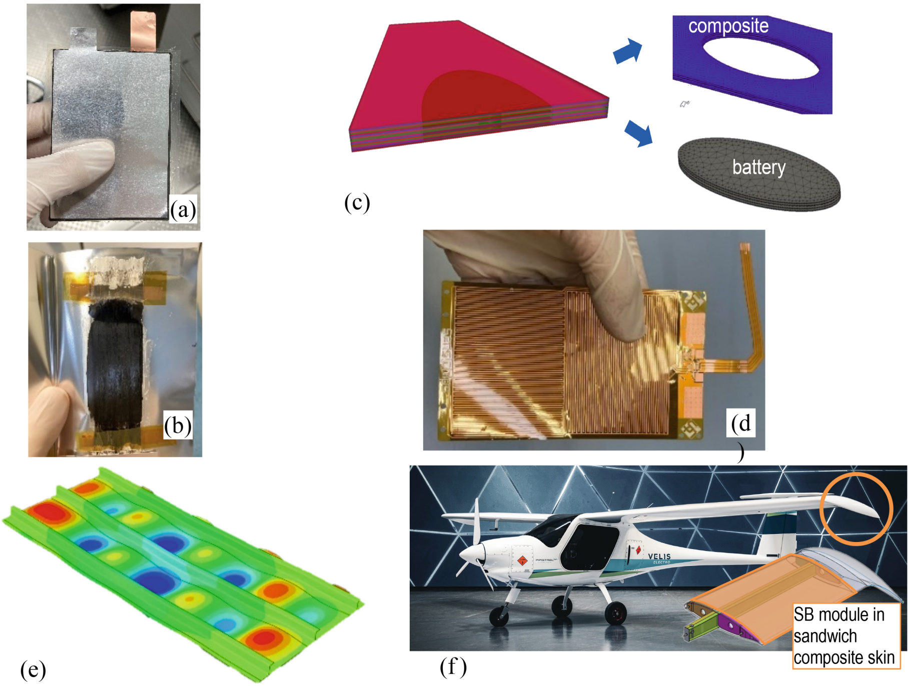

Fig. 1. SB cell developments in SOLIFLY/MATISSE: SB cell concepts: laminate cell (a), coated CF cell (b); numerical strategy for structural integration into solid CFRP composite (c); integrated sensor/current collector foil of smart SB cell (d); numerical simulation of the SOLIFLY SB panel demonstrator (e); SB integration (indicated) into a detachable wingtip for a full-electric light aircraft (f). (a)–(c) Reproduced with adaptations from [9], (d)–(e) Source: Authors, (f) Image courtesy of Pipistrel, reproduced with permission.

optimized by using more energy-dense anodes (going from graphite to Si-graphite and ultimately Lithium metal) and by reducing the weight of passive components. This shows the potential of SB technology to achieve up to 1 kWh per litre and extra kg, doubling the maximum effective ED of monofunctional Li-ion batteries, and a packaging weight efficiency (ΔGED:GED) of around 250% to 350% (always below 100% for monofunctional batteries). These results promise a massive decrease of battery weight penalty. Conversely, even a completely mass-less energy storage could be created by matching the SB and structural densities, at the expense of its absolute energy content.

Assessing the multifunctional benefits of SB at aircraft structure level needs to consider its impact not only on energy storage and weight but also on aerodynamic forces and moments. The design and demonstration of the MATISSE SB wing tip [10] will provide first time tangible results for airworthy SB integration that will support virtual upscaling for large aircraft.

Table 2. Actual and projected energy KPIs for SOLIFLY SB technology

SB integrated into CFRP solid laminate composite		GED [Wh/kg]	VED [Wh/l]	ΔGED [Wh/Δkg]
Sota SOLIFLY SB low density NMC cathode, Gr anode	typical usable energy content	50	88	518
	maximum verified energy content	115	200	1200
Evolution of SB electrochemistry	dense NMC cathode, Si/Gr anode	220	580	560
	ultra-light passive components	290	630	1020
	using Li-metal anode	375	1000	920

4 Conclusion

Structural battery technology has the potential to overcome the limits found in conventional battery energy storage due its packing efficiency greater than 100% and energy storage capability of around 1 kW per litre or kg added weight. A wide range of challenges still needs to be tackled for SB, including further improvement of electrical and mechanical performance, reducing the large gap between SB cell and structural life, improving sustainability and repairability e.g. by using bio-based and/or thermoplastic materials. The EU-funded research projects SOLIFLY and MATISSE undertake great efforts to develop further and mature SB technology for aerospace applications and to pave the way for its uptake supporting climate-neutral aviation.

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Manufacturing and Assembly of Modular and Reusable EV Battery for Environment-Friendly and Lightweight Mobility

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Abstract. Range anxiety is one of the key reasons why Battery Electric Vehicle (BEV) market still has not fully taken off. Users demand EV to be able to fast-charge and travel long distances with short breaks. Ultra-Fast charge appears, therefore, as one of the milestones to reach for widespread electrification. However, such amounts of power, even during short time, require of a proper dimensioning of the system. Thus, the battery must be prepared for such events, controlling cell status during operation to drop the effect of both fast battery degradation and potential dangerous events. Consequently, an increased battery performance requires an adapted battery thermal management system (BTMS) to ensure an uniform temperature distribution in the battery pack especially during fast and ultra-fast charging, to ensure the longest possible battery lifetime. In this paper, the influence of different thermal conductivities of the BTMS on the average battery cell temperature are investigated. The simulation bases on a hybrid 3D/1D model of a module which enables an easy comparison of the impact of the thermal conductivity of the battery cell, thermal pads, heat spreader, and the cooling channels design. The results can be used to determine which measurements have a particularly high influence on the performance of the cooling system. Furthermore, it is possible to identify potential to reduce the weight of the system and keep the environmental impact as low as possible.

Keywords: Battery thermal management · cell ageing · lightweight mobility · simulation · electric vehicle

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1 Introduction

BEV are the key technology to decarbonise road transport, a sector that accounts for around 16% of global emissions. To accelerate the introduction of BEVs into the mass market, the MARBEL project was launched to develop an ultra-high-performance battery for cars with a higher energy density, shorter and more efficient fast charging, and a longer lifetime [1]. Lithium-ion batteries are used to achieve the required energy density [2]. Since the performance, safety and lifespan of the battery cells are affected by their operating temperature a BTMS is needed to keep the operating temperature within a range of 15–35 °C with a maximum temperature spread of 5 K at battery cell level [3, 4]. The most common systems rely on air-based, liquid-based, phase change material, heat-pipe based BTMS or a combination of these [5]. This allows to combine the advantages of each system.

2 Thermal Management System

The battery pack consists of 32 modules which contains 12 battery cells each. In Fig. 1 an explosion view of the module thermal management system without the housing is shown. On the top of the battery cell are the welded aluminum terminals that serve as both electrical and thermal connection. The side compression pad absorbs the volume change of the battery cell during the lifetime and ensures uniform pretension. On the opposite side the L-shaped aluminum fin distributes the thermal energy across the surface and dissipates it downward to the cooling plate. Thermal pads are placed between the battery cell and the fin to reduce thermal resistance and compensate the tolerances. This described design represents the smallest increment of the thermal management system (TMS).

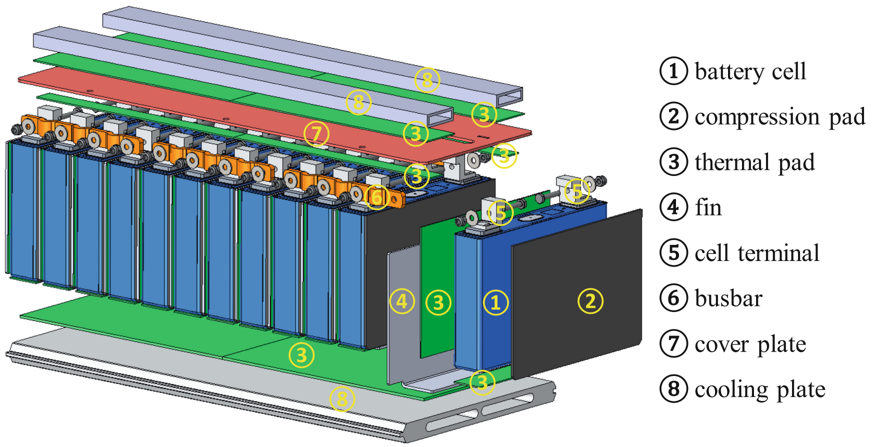

Fig. 1. Explosion view of the module thermal management system. Reproduced with permission from [AVL Deutschland GmbH], copyright [AVL Deutschland GmbH], [2024].

For the module, the battery cells with the compression pads, the compression and thermal pads and the fins are stacked and connected to the busbars. On top of them there is a cover plate with thermal pads on both sides to provide a good thermal conductivity between the water-cooled top cooling plates and the busbars. With this design it is possible to dissipate the heat generated by the busbars and the terminals into the top cooling plates and reduce the temperature spread within the battery cell [6]. As with conventional cooling systems, there is also another water-cooled plate with a thermal pad on the bottom of the battery cell stack. With this design the cooling channels are integrated in the battery pack housing to integrate two functions in one part to achieve the weight goals.

3 3D Simulation of the TMS

A 3D conjugate heat transfer computational fluid dynamics (CFD) simulation was performed with the software STAR-CCM+ using a steady Reynolds Averaged Navier Stokes (RANS) approach. For the coolant flow a 2nd order numerical scheme was used together with a K-epsilon turbulence model. The near wall regime was treated with a two-layer approach to resolve the boundary layer effects. In the solid parts the energy equation is solved together with an additional source term to include the ohmic joule heating due to electric current flows at the busbars and terminals also using 2nd order numerical scheme. An average mesh size of 2–4 mm is employed to resolve the thermal paths using polyhedral and thin prismatic finite volume numerical cells. The analysis of the temperature distribution is performed for one module and considers a heat release of 10 W per battery cell (2C charge). An electrical contact resistance of 25 μOhm between the busbar and the terminal is considered. The flow rate of the cooling medium is symmetrical and is 2.03 l/min for the upper and lower cooling plate. The starting temperature is 25 °C for the battery cell and the coolant. Table 1 summarizes the material parameters used.

Table 1. 3D simulation parameters

Part	Material	Density (kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)
Battery cell	-	2100	1100	5/20/12 (x/y/z)
Terminal	Aluminium	2700	f(t)	180
Busbar	Copper	8960	f(t)	401
Compression pad	Aerogel	350	400	f(t) (0,02–0,09)
Thermal pad	Silicon	2100	2000	3
Fin	Aluminium	2700	f(t)	180
Cover plate	Aluminium	2700	f(t)	180
Cooling plate	Aluminium	2700	f(t)	180

For a better assessment of the temperature distribution, Fig. 2 shows an exploded view of the smallest increment of the cooling system in a steady case. The cold spots of the battery cell are located on the poles and on the underside. Due to the fin, the temperature distribution on the left side is more homogeneous than on the right. This is where the highest temperature is found. Due to the combination of a top and bottom cooling concept, the maximum temperature spread does not exceed 5 K in the battery cell and is smaller than 5 K in the whole pack when the average battery cell temperature is considered.

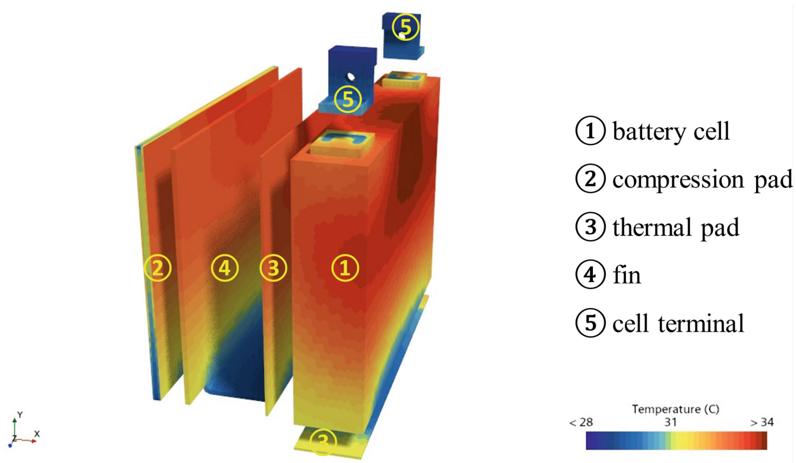

Fig. 2. Temperature distribution in one battery cell of the module simulated with STAR CCM+

4 Model Order Reduction

To increase the computational speed and to investigate the influence of different parameters on the battery cell temperature, a 1D simulation of the battery cell is combined with a 3D thermal simulation. The basis is the model developed by Guitart et al. which has good agreement with the practical experiments and the 3D simulations from Sect. 3 [7]. The starting temperature of the simulation is 26.5 °C for the module and 20 °C for the coolant with a total flow rate of 4.06 l/min (Table 2).

The parameters represent a maximum approach with high thermal conductivities (HC) of the thermal pads and fin material. For the thermal conductivity of the battery cell 20% higher values are considered. In the simulation the different parameters are varied individually to determine the effects on the average temperature. In a further simulation, the cooling channels are modified (Fig. 4). Finally, the parameters with the largest impact on the mean battery cell temperature are combined to investigate the potential of the TMS. In Fig. 3 the average battery cell temperature is shown with the error indicators visualizing the minimum and maximum battery cell temperature in the whole module.

Table 2. Variation of simulation parameter for case study

Part	Low thermal conductivity (W/mK)	High thermal conductivity (W/mK)
Battery cell	5/20/12 (x/y/z)	6/24/14,5 (x/y/z)
Thermal pad	3	20
Fin	180 (Aluminium)	401 (Copper)

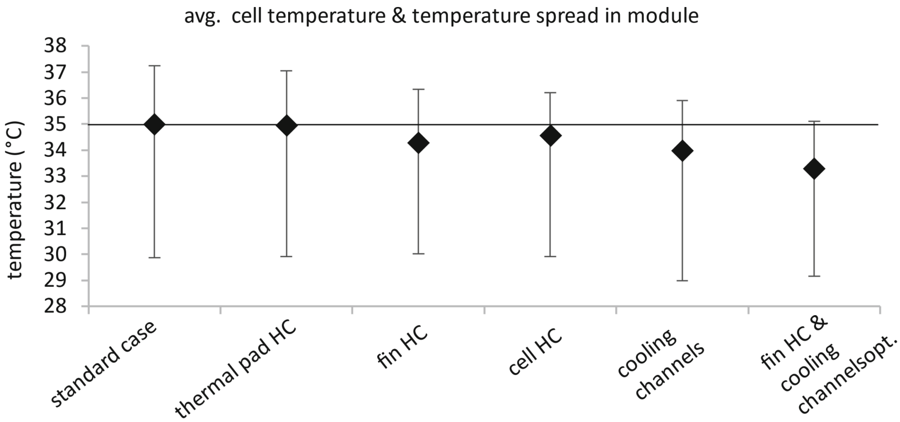

Fig. 3. Temperature evolution with different simulation parameters

The standard case represents the simulation with the low thermal conductivities and with the standard cooling channels. A higher thermal conductivity of the thermal pads does not decrease the average battery cell temperature significantly. With the copper fins the average battery cell temperature in the module can be reduced by 0,71 K with a more homogeneous temperature distribution at battery cell level. The high thermal conductivity battery cell has a lower impact on the average battery cell temperature while the temperature spread remains the same. When the number of cooling channels is increased as shown in Fig. 4 the average battery cell temperature is decreased by 1,01 K but increases the temperature spread at battery cell level.

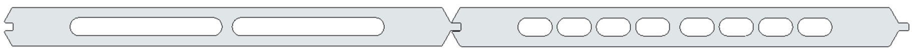

Fig. 4. Cooling channel, standard layout (left) and optimized (right)

With the combination of the high fin thermal conductivity and the optimized cooling channel design the average battery cell temperature can be decreased by 1,70 K which corresponds the linear add-up of both measures. The temperature spread on battery cell level is also the lowest compared to the other setups (7,06 K).

5 Discussion

Thermal pads have the smallest influence on the average battery cell temperature and are not the bottleneck in the TMS. The higher thermal conductivity does not lead to a higher temperature difference between the coolant and the fin and therefore does not enhance the cooling performance. This effect can be reached by a thicker fin, or a material with higher thermal conductivity like copper. Due to the higher temperature difference of the bottom of the fin to the coolant, more energy is transferred. On the contrary, this leads to an earlier increase of the coolant temperature, which results in a higher temperature spread within the module. This can be countered with an adapted fin thickness, if thin fins are used at the cold side of the module with gradually increasing thickness towards the warm side. The increase of the battery cell thermal conductivity has a less significant impact on the temperature spread within the module, compared to the fins and shows the relevance of further increasing thermal conductivity· Apart from the thermal conductivity of the TMS components, the simulation points out the importance of the cooling channel design. By dividing large cooling channels into smaller ones, a lower average battery cell temperature can be achieved for the same installation space. The heat transfer to the cooling medium is the bottleneck in this TMS design. In the standard case, the energy dissipated from the battery cell cannot be transferred to the fluid, which results in the higher average battery cell temperature and a bigger temperature spread within the module. At the same time, the temperature spread within the module remains comparatively small, which also supports this conclusion. For future TMS, it is an option to adapt the heat transfer by different cooling channel designs and to achieve a lower and more uniform temperature distribution in the battery pack. The combination of the higher thermal conductivity and the optimized cooling channel design leads to the lowest average battery cell temperatures with the highest temperature spread within the module. Adjustment of the heat transfer or fin thickness is required to achieve a more homogeneous temperature distribution in the pack.

The results shown are valid for the TMS presented.

6 Conclusion

In the paper it can be shown that with a calibrated hybrid simulation model the influences of the elements of the TMS can be investigated to reduce the battery cell temperature and spread. The influence of the thickness and thermal conductivity of the thermal pads is small in absolute terms. A higher thermal conductivity or thickness of the fins reduces the average battery cell temperature. For a homogeneous temperature distribution in the pack, different thicknesses of the fins should be used. The heat transfer of the coolant has the greatest influence on the battery cell temperature and can be controlled by the geometry of the cooling channels. With an adapted cooling channel design, the temperature and the temperature spread inside the battery pack can be controlled and will decrease the aging of the battery cells for a longer lifetime of the whole battery pack.

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Effects of Traffic Signal Coordination on Traffic- and Emission-Related Evaluation Parameters

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Abstract. A good coordination of traffic signals can reduce waiting times, the number of stops and accelerations, and thus increase travel speeds, which can lead to a reduction in fuel consumption and air pollutant emissions. To investigate the effects of traffic signal coordination on traffic and emission parameters, simulation studies are advantageous over time-consuming field tests to quantify and evaluate quickly, safely and cost-effectively a large number of different input variables, such as intersection distances, traffic volumes and different signal control configurations. This paper describes the findings of an extensive simulation study in which a microscopic traffic flow simulation model was coupled with an emission model. Through the simulation of a range of scenarios, the model is used to investigate the influence of inter alia traffic volume, signal coordination schemes and signal parameters on carbon dioxide, nitrogen oxides and particulate matter emissions along an arterial road equipped with a series of traffic lights. Results showed that shorter distances between the signalized intersections led to about 20% higher emission values. Furthermore, different cycle times and their effects on emissions were investigated, whereby higher cycle times led to lower values of about 14% less emissions.

Keywords: coordinated signal control · emission modelling · microscopic traffic flow model

1 Introduction and Motivation

In urban road traffic management traffic signal control has become the most important operational measure, as poor traffic signal timing largely contributes to traffic congestion and delay. In order to achieve a high traffic quality, the green times of a series of traffic lights are coordinated. This realisation of a "green wave" allows the majority of vehicles to pass several signal-controlled intersections without having to stop. Although the potential of "green waves" to reduce travel time losses is widely acknowledged, the side effects on resulting vehicle emissions are far less researched. Most studies only consider emissions at individual intersections, see [1, 2]. When considering the effects of traffic signal coordination, usually only the emissions of single vehicles are measured using on-board devices and portable emission measurement systems in the course of time-intensive measurement runs or immissions are measured at special hotspots in the

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traffic network. Details about the composition of the vehicle fleet are often not provided, which makes it difficult to compare the results of different studies. [3] used a portable emission measurement system to compare the pollutant emissions of a single vehicle with and without coordinated traffic signal control under comparable traffic conditions. An emission reduction of about 50% was calculated for a perfect "green wave" compared to a "red wave". Since environmental performance measures become more important in decision making of traffic signal control, there is still a demand for further investigations of effects of traffic signal coordination on traffic- and emission-related evaluation parameters.

To study effects of traffic signal coordination, field-measurements fall outside the scope, as they are time-consuming, costly to conduct and not transferable. Hence, simulations are beneficial, as they guarantee a faster, safer, and cheaper way to test a high number of different input variables, such as intersection and road geometry, traffic volume and traffic signal settings. Since the emissions depend very much on microscopic events, such as accelerations and decelerations, the simulation has to consider precise vehicle movements, as suggested in [4]. Therefore, suitable models have to provide a combination of microscale traffic and emission simulation. This paper reports on a computational study in which a microscopic traffic simulation model is combined with an emission model to assess traffic and emission-related evaluation parameters.

2 Methodology

The aim of this paper is to investigate the influence of the coordination quality of signal control as well as various boundary conditions on vehicle emissions within a simulation study. Since vehicle-related emissions are strongly dependent on dynamic driving events such as acceleration and deceleration, the simulation must be able to accurately represent vehicle movements. For this reason, we combined a microscopic, behaviour-based traffic flow simulation model (PTV VISSIM) with a microscale emission model for air pollutants (PHEM - Passenger Car and Heavy Duty Emission Model, [5]) to quantify traffic parameters and emissions. PHEM is based on a vehicle longitudinal dynamics model for calculating the current drive and engine power and can be classified as a map-based emission model in which the emissions are stored in three-dimensional maps via engine speed and engine power. When coupling these two types of models, two different methods of investigation are possible. In the first option, a real street segment can be modelled in detail, and a limited number of scenarios can be simulated. Here, precise knowledge is obtained about the coordination quality of a specific road segment and the vehicle emissions that are generated along this arterial can be quantified, as described in [6]. However, there is a lack of generally valid transferability of the results to classify emission values for different road segments and under different traffic environment. The second option can close this knowledge gap by modelling and considering a large number of simplified scenarios in the simulation, see also [7]. Therefore. This research methodology is chosen in the present work, as it leads to transferable findings that are not limited to specific street segments.

Three simplified route scenarios of an urban arterial road with five consecutive signalised intersections were modelled in the simulation study with constant intersection

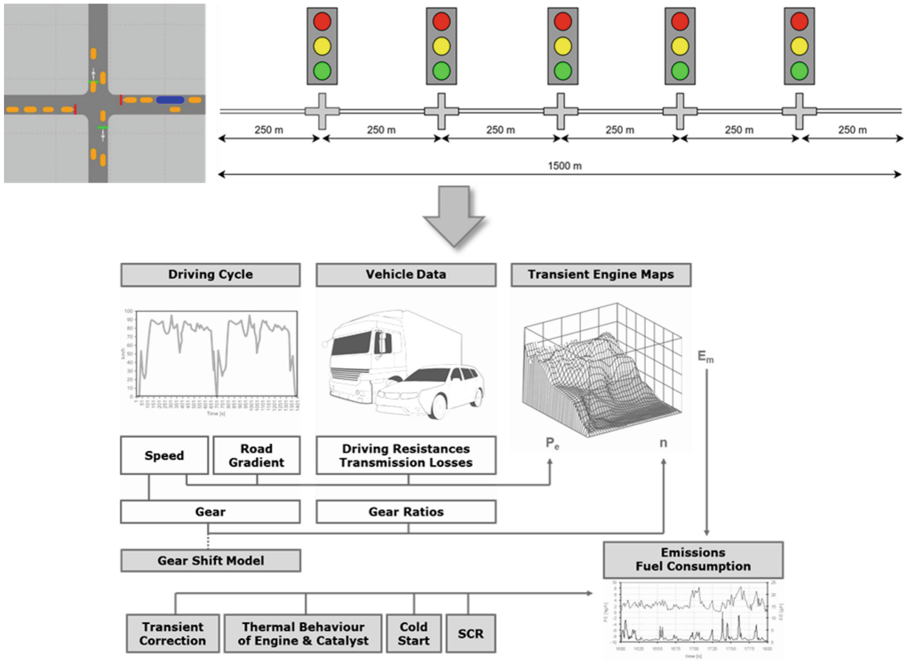

Fig. 1. Simulation framework of microscopic traffic flow model VISSIM, (Source: Haberl, M.) and microscale emission model PHEM [5], (Source: adapted based on Hausberger, S).

distances of 250 m, 500 m and 750 m. Since larger intersection distances are rarely found in urban road networks and according to the HBS [8] it is recommended not to exceed larger intersection distances when planning coordination. In many cities and municipalities, motor vehicle traffic causes major problems, which are reflected in accidents, noise and air pollution, see [9]. One way to reduce the pollution is to lower the speed limit in urban areas. Since speed limits with 30 km/h offer a few advantages, more and more cities and municipalities throughout Europe want to establish 30 km/h speed limits. Accordingly, simulation scenarios with 30 km/h and 50 km/h were investigated to examine and compare emissions. With an intersection distance of 250 m, see Fig. 1, the entire arterial has a length of 1,500 m, whereby one lane per direction of travel was modelled. A simple signal timing plan with two phases and a green split of 50% with fixed-time controlled signal programs was created. According literature review and preliminary studies, such as [10], significant variables of traffic and infrastructure were defined for the simulation framework development, including traffic volume, intersection distance, heavy good vehicle share, speed limit and signal timing settings such as cycle time and offsets between signalized and coordinated intersections. The aforementioned variables were taken into account in the simulation study design in order to cover a series of parameters and to be able to investigate their influence on the traffic parameters and the resulting emissions along the coordinated route, see Table 1.

The simulation duration was 3,600 s per simulation run and the driving trajectories of all simulated vehicles were transferred from the microscopic traffic flow model

Table 1. Simulation study design and parameter ranges for the simulation scenarios.

Parameter	Parameter Range	Extent
Intersection Distance [m]	250 m, 500 m, 750 m	N = 3
Speed [km/h]	30 km/h, 50 km/h	N = 2
Traffic Volume [veh/h]	250 veh/h, 500 veh/h, 850 veh/h, 1000 veh/h,	N = 4
Heavy Goods Vehicle Share [%]	0%, 5%, 10%, 15%	N = 4
Cycle Time [sec]	60 s, 80 s, 100 s	N = 3
Offset Time [sec]	0 s, 10 s, 20 s, …, 70 s, 80 s, 90 s	N = 6, 8 or 10 according Cycle Time

via vehicle log files to the emission model. An important feature of the selection of emission model PHEM for this simulation study was that the results are representative for a complete vehicle fleet and not just a limited sample of vehicle types. The vehicle models available in the PHEM dataset include not only passenger cars but also the fleet composition of light and heavy duty vehicles. In this study, the Austrian vehicle fleet of 2023 was used. A multiple simulation with 5 runs was carried out to account for the stochasticity of the simulation results within the microscopic traffic flow simulation. Hence, a total of 11,520 individual simulations were carried out and evaluated.

3 Results and Discussion

Through the simulation of a range of scenarios, the model framework was used to investigate the influence of traffic intensity, signal coordination schemes and signal parameters on carbon dioxide, nitrogen oxides and particulate matter.

Table 2. Correlation coefficient r [$\bar{x}$ (σ)].

Variables	CO_2	NO_X	PM
Avg.Speed [km/h]	−0.887 (σ = 0.0355)	−0.8426 (σ = 0.0679)	−0.6389 (σ = 0.1376)
Acc.Noise [m/s^2]	0.7969 (σ = 0.0717)	0.7297 (σ = 0.0499)	0.5308 (σ = 0.0397)
a_pos [m/s^2]	0.2689 (σ = 0.3079)	0.2256 (σ = 0.2969)	0.1318 (σ = 0.2102)
a_neg [m/s^2]	−0.394 (σ = 0.1768)	−0.3204 (σ = 0.2308)	−0.2373 (σ = 0.1892)
pAcc [%]	0.6154 (σ = 0.1245)	0.5804 (σ = 0.1184)	0.4347 (σ = 0.1488)
pDec [%]	0.4633 (σ = 0.2286)	0.4514 (σ = 0.2218)	0.319 (σ = 0.1837)
pCruise [%]	−0.9041 (σ = 0.0352)	−0.8719 (σ = 0.0439)	−0.6483 (σ = 0.1254)
pStop [%]	0.6778 (σ = 0.0843)	0.6538 (σ = 0.0823)	0.4981 (σ = 0.1413)
delay [sec]	0.8765 (σ = 0.0492)	0.8295 (σ = 0.0762)	0.6416 (σ = 0.1529)

Besides emissions as evaluation parameters, also traffic-related parameters, such as average speed (Avg.Speed), delay (sec), acceleration noise (Acc.Noise), percentage of stops, acceleration, deceleration and cruising (pStop, pAcc, pDec and pCruise) as well as positive and negative acceleration (a_pos and a_neg) were investigated. To examine how strongly the variables, relate to each other, we performed a correlation analysis between the traffic related variables and the emission factors. Table 2 shows the mean values ($\bar{x}$) and the standard deviation (σ) of the correlation coefficient r. CO_2 shows stronger correlations with the traffic variables then NOX and PM. The average speed, delay, acceleration noise and percentage of cruising can explain the emission values of carbon dioxide (CO_2), nitrogen oxides (NO_X) and particulate matter (PM) the best.

Figure 2 shows the average CO_2 emissions per vehicle for a vehicle fleet of 90% cars and 10% HGV as a function of traffic volume, for various cycle times and intersection distances. On the basis of the simulation results, polynomial regression functions were estimated, which could show a higher coefficient of determination R^2 than comparatively linear regression functions. Since the R^2 is always greater than 0.9, the functional relationship can be confirmed. The functional equations are listed in the following diagrams and thus also enable the determination of CO_2 emissions in g/km for alternative traffic volumes by interpolation. It is obvious that the pollutant emissions under the condition of a speed limit of 50 km/h are significantly lower than in the scenarios of coordinated routes with speed limit of 30 km/h. At a low traffic volume of 250 veh/h or 500 veh/h, no significant differences in terms of CO2 emissions can be identified between the different cycle times and intersection distances, as the coordination works equally well at optimal offset times. At high traffic volumes the emissions at scenarios with short cycle times of 60 s. are about 8% higher compared to emissions of cycle times of 80 s. and about 13% higher than emissions of cycle times of 100 s.

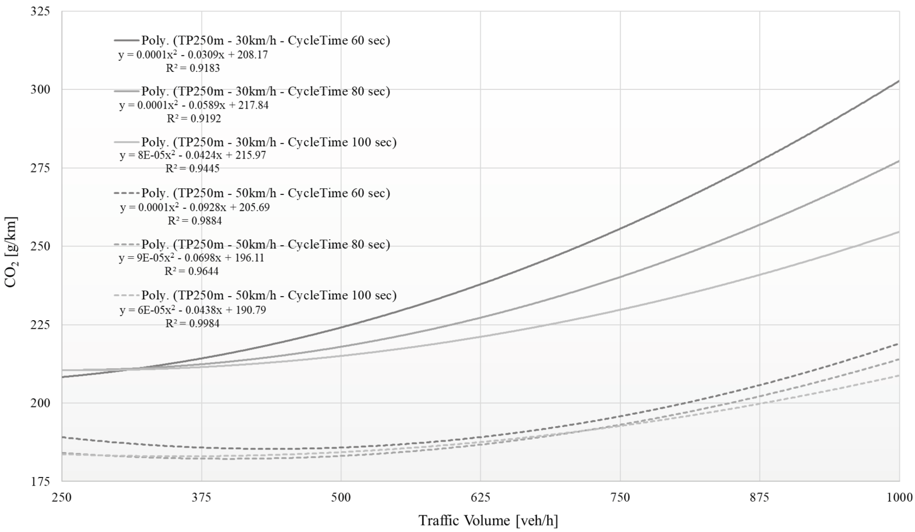

Fig. 2. Average CO_2 emission for 90% cars and 10% HGV as a function of traffic volume, for various cycle times and intersection distances.

4 Conclusion and Outlook

This paper reported the influence of traffic signal coordination on air pollutant emissions (CO_2, NOx and PM) was investigated. A microscopic traffic simulation model (VISSIM) was coupled with the emission mode PHEM. A simplified setting was considered, consisting of an urban arterial road with five consecutive traffic signals. Through the simulation of a range of scenarios, the influence of the traffic volume, the signal coordination scheme and signal parameters on emissions and traffic related variables was investigated. The average speed, delay, acceleration noise and percentage of cruising can explain the emission values the best. It was found that, the largest potential emission reduction occurs when traffic intensities are close to capacity, especially for street segments of 30 km/h speed limit. In this context the cycle time was found to have a significant influence on emission values. In comparison the emissions at street segments of 50 km/h speed limit are considerable lower. The simulation results from the extensive simulation study allow further in-depth investigations on the influence of coordinated road segments on emissions and will be tested for real world scenarios.

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Modelling Cities' Pathways to Zero-Emission Urban Mobility Through the Simulation of 5 European Cities

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Abstract. This paper focuses on the results of a study that modelled European cities' pathways to zero-emission urban mobility by 2030 through the development of potential transition scenarios. Each scenario is built on set of sustainable policy measures, whose impacts is quantified through a series of indicators as output results. The assessment is realized through MOMOS, a quantitative tool which allows to simulate and quantify in a simplified way the impacts of potential mobility transition scenarios in cities. Four potential scenarios, each one with a different focus and a specific combination of policy measures, have been simulated and applied to five European cities. The main output of the paper consists in the calculation of the CO2 emissions reduction associated to each scenario, and of a series of transport, environment, social, and economic indicators.

Keywords: Zero-emission transport · Sustainable transport policies · Transport modelling · Green Deal target · Sustainable cities and communities · Clean mobility options

1 Introduction

Between 1990 and 2019, transport sector emissions have increased by around 24% [1] and cities are reported to be responsible for more than 70% of GHG emissions [2], with urban transport estimated to constitute between 20% and 50% of total urban energy consumption (excluding industry) [3].

Cities need to develop and implement coherent and challenging plans that should be focused on the achievement of the EU objectives for urban transport. The EU Green Deal [4] calls for a 90% reduction in greenhouse gas emissions from transport, for the EU to become a climate-neutral economy, while also working towards a zero-pollution ambition.

To achieve this systemic change, transport modes need to be more sustainable, wider alternatives should be offered as part of a multimodal system, and the right incentives should be put in place to drive the transition.

What is needed is an integrated strategy composed of sustainable mobility policies, evaluated in a scientific and measurable way, and flexible enough to accommodate for

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future changes. This is a viable way to offer cities, where resources are always limited, a potential solution to manage their mobility problems, while providing efficient transport solutions (on one hand) and fighting the consequent negative effects (on the other).

Given this challenging context, the objective of this paper is to model European cities' pathways to zero-emission urban mobility by 2030 through the development of potential transition scenarios. Each scenario is built on a different set of sustainable policy measures, whose impacts are quantified through a series of indicators as output results.

The analysis keeps a high-level character with some obvious limitations (data availability, input estimation, etc.) and underlying assumptions but allows to demonstrate how the implementation of sets of transport policy measures would lead to a sustainable mobility transition.

The paper does not intend to present the most likely outcome nor attempt to forecast the future of urban mobility. Rather, it shows potential future pathways and scenarios given a context of large uncertainty around policies/measures and general developments/trends occurring in different European cities.

Five different metropolitan areas have been analyzed: Brussels-Capital Region, Madrid, Greater Manchester, Milan and Warsaw.

2 Methodology

2.1 General Approach

This paper illustrates a quantitative analysis of different possible pathways to zero-emission urban mobility in 2030 in five European cities. To accomplish this goal, the MOMOS (Sustainable Urban MObility MOdel) assessment tool has been employed to simulate the outcomes of different mobility transition scenarios.

Using MOMOS, it has been possible to quantify the impacts of the pathways to zero-emission mobility on the transport, environment, and safety domains, estimating the economic resources needed to drive such transition.

Four potential scenarios have been simulated. Each one based on a specific combination of policies measures that have been selected considering the main EU initiatives in terms of sustainable urban mobility (e.g., CIVITAS, ELTIS, etc.).

The first two scenarios have a well-defined focus: incentivize active and collective mobility (S01) and fleet electrification (S02). The third one (S03) combines all policy measures from the previous two scenarios. The fourth one (S04) not only applies all policy measures but also extend their reach to demonstrate the challenge of achieving a zero-emission urban mobility already by 2030.

All scenarios are applied to the five European cities. Each one has been defined upon an in-depth data collection to reproduce its characteristics at the base year.

The MOMOS simulation of the transition scenarios returns a series of quantitative indicators as outputs. Results are provided for both the horizon year (2030) and the base year (2019) that is used as comparison.

Of course, the key output indicator is represented by the Greenhouse gases emissions from transport. Moreover, a series of core indicators provides a thoroughly description of the mobility situation in 2030: transport behaviour, transport activity, electric vehicles uptake, air pollutant emissions from transport, and road safety. Both passenger and freight compartment are considered.

In addition, a multi-criteria economic analysis estimates the costs and impacts in monetary terms associated to each scenario. Costs (and revenues) for the city, the transport users, and the freight operator are simulated, as well as the external costs savings resulting from reductions in CO2 and air pollutant emissions, accidents, and noise.

2.2 Input Data

To properly represent the city's characteristics at base year, the MOMOS tool requires a comprehensive set of input data. Input data retrace, in the most accurate way possible, the city circumstances, including both socio-demographic aspects, and of course all urban mobility features. The collected inputs include: urban characteristics (population, economy, etc.). Urban mobility (modal split, motorization rate, congestion, etc.), public transport (offer, infrastructure, etc.), transport infrastructure (bike lanes, charging stations, etc.) parking, shared mobility, traffic control and management (LEZ, LTZ, traffic calming, etc.), vehicle fleet composition.

2.3 Design of the Transition Scenarios

Four potential transition scenarios have been designed through different combinations of sustainable policy measures. These measures comprehensively cover the range of options that cities currently have available to lead the transition to sustainable urban mobility.

Each policy measure is defined through specific inputs parameters and targets determining its intensity over the course of time, the expected initial year of implementation, and the necessary ramp-up period to achieve full effect.

The following four potential scenarios have been considered:

- Scenario 1 (S01) "Active and Collective": more sustainable travel behaviour by upgrading the public transport system, incentivizing the usage of active and shared mobility, and implementing pricing and regulation schemes.
- Scenario 2 (S02) "All-electric": focused on fleet electrification as the core element for a sustainable transition.
- Scenario 3 (S03) "Everything all at once": combining all available policy measures that have been implemented in the previous two scenarios.
- Scenario 4 (S04) "(E)Mission: Zero": not only applies all the measures included in scenario 3, but also push to the limit a series of targeted policies with the aim of getting as close as possible to the zero-emission urban mobility target by 2030.

The list of sustainable policy measures that have been applied to the four scenarios is included in Table 2.

To attain the sustainable urban mobility transition of the potential scenarios, each policy needs to be constructed (and calibrated) using a series of parameters and pre-identified targets. Such targets have been identified by taking into account what has

Table 2. List of policy measures applied to scenarios. In brackets, if applied to Scenario 1 or 2

Group	Input data
Vehicle fleet and charging infrastructure	Electric cars penetration (2), Electric energy refueling infrastructure (2), Green public transport fleet (1,2), Green logistics fleet (2), Cooperative ITS (2),
Innovative and shared mobility services	Bike sharing (1), Car sharing (1), Moped sharing (1), Micro mobility (1), MaaS (1), DRT (1)
Transport infrastructure	Cycling network (1), Bus network (1), Tram network (1), Metro network (1), Park & Ride (1)
Traffic management and control	Prioritizing public transport (1), Limited traffic zones (LTZ) (1), Low emission zones (LEZ) (1,2), Traffic calming (1), Pedestrian areas (1)
Transport avoidance	Working from home (1,2), Car-free days (1)
Pricing schemes	Congestion and pollution charging (1,2), Parking pricing (1,2), Public transport fare (1)
Urban logistics	Urban delivery centers (1), Delivery and servicing plan (1), Cargo bikes (1)

already been identified by the cities in terms of their mobility future (e.g., SUMP objectives, specific goals, fleet evolution forecasts, etc.) as well as what is needed to properly address the zero-emission urban mobility by 2030.

Also, it is worth underlying that scenario 4 includes a few policies that are built to reach notably higher and extremely aspiring targets. Indeed, this is the only way to get as close as possible to the goal of a zero-emission urban mobility in 2030.

Finally, the scenarios simulated in this paper follow the assumptions related to the vehicle fleet composition with an ambitious penetration of innovative vehicle technologies, building on the assumptions of the EU "Fit for 55" strategy [5].

3 Results and Discussion

The results of this paper consist of a series of quantitative indicators. Indicators are calculated for each scenario at the simulation's horizon (2030) as well as compared to the values at base year (2019).

Of course, as the overall objective of is to simulate pathways to a zero-emission urban mobility by 2030, the key indicator is represented by the reduction in CO2 emissions. In addition, a series of core indicators provide a full picture of the scenarios simulations by outlining their effects on the transport, environment, and social spheres.

Considering Greenhouse gas emissions, all scenarios generate major reduction, though the extent of these reductions is not the same in all scenarios. The implemented policies result in a reduction of about 25% in both S01 and S02, in which the cities see total reductions - i.e. including regulatory changes and technological improvements -

in the order of magnitude of 60%. In S03, total reductions are only somewhat higher (around 65%) due to the strong effect of the shared common policies and the partially mutually exclusive nature of the implemented ones. S04, being the most ambitious, generates the highest reductions of more than 90%, clearly showing what large-scale reductions would be technically possible and could be achieved in a relatively short period of time putting in place large efforts and changes in mobility habits.

In all scenarios and cities, the modal share of public transport and active travel increases, whereas the share of private car use decreases. This change is strongest in S04 and weakest in S02. Similarly, distances covered by private cars and car ownership decrease in the same manner. The uptake of battery-electric vehicles (BEV) reaches its highest levels in S04, with more than 30% fleet share, and less high in S02 and S03. In S01, where no dedicated policy is applied, the BEV uptake does not go beyond the uptake driven by EU/national regulation. For freight vehicles the trend is similar, though the fleet share of electric vehicles is much higher than for private cars, with more than two in three light duty vehicles (LDV) going electric. For heavy duty vehicles (HDV), the share of electric trucks stays below 5% in the first three scenarios but reaches close to 40% in S04. Also, in terms of freight, their Vehicle-kilometres increase in all scenarios despite a decrease in HDV traffic paired with a shift to cargobikes.

Because of the changes described above, air pollution caused by urban transport decreases significantly.

Shifting from private car use to active travel, public transport and from fossil-fuel powered vehicles to electric vehicles reduces overall energy consumption from transport in all scenarios. While electricity demand increases strongly between 2019 and 2030 due to the electrification of motorised transport, fossil fuel consumption decreases by more than 90%. As a result, overall demand for energy from transport is reduced across scenarios and by as much as two thirds in S04.

Finally, road traffic collisions and therefore injuries and fatalities decrease in all scenarios. The reduction is however much more pronounced in the scenarios encouraging active travel and public transport.

While implementing the measures results in important costs across all scenarios and cities, these also generate big (co-)benefits from improved road safety, reduced GHG emissions and air pollution and less noise, with the largest benefits coming from safer roads and the reduction in GHG emissions. The cumulative costs per scenario and city range from 940 to 2,800 € per inhabitant, and the benefits in the form of savings range from 790 to 4,030 €. In all scenarios but S02, all cities see benefits outweigh the costs. S04 is the costliest of all scenarios, but it is also the one that generates the highest benefits.

Full results of the study are available here: https://cleancitiescampaign.org/research-list/e-mission-zero/

4 Conclusions

This paper has been able to assess the transition towards a zero-emission urban mobility by 2030 in five different European cities. Whereas the simulation did not have the ambition to present the most likely transition outcome, it showed potential future pathways in a context of large uncertainty (policies, trends, etc.) while demonstrating the high efforts needed to accomplish such challenging goal. The implementation of sets of policy measures also showed their impacts on mobility, environment, and safety.

The results of the simulation showed that reaching the zero-emission target already by 2030 is an extremely challenging target, considering the magnitude of the needed interventions, and the very short time in which these changes need to be implemented.

The simulation of S04 suggests that with a set of very ambitious and targeted policies, a strong reduction of CO2 emissions is attainable. However, getting there implies quite drastic changes in the mobility behavior of citizens especially in terms of their modal choice (giving up the usage of their car in favor of alternative modes). Of course, this also needs to be accompanied by a very strong uptake of zero-emission vehicles in the fleet. High fleet renewal, decarbonization of last-mile delivery with cargo-bikes and increased efficiency of freight transport sector are essential too.

Although they remain further away from the zero-emission target, S01 and S02 have both shown that a considerable emissions reduction is possible while focusing the efforts on, on one hand, the improvement of urban transport infrastructure, shared mobility, and traffic regulation (S01) or, on the other hand, of the uptake of electric vehicles in the fleets (S02). These results suggest that different pathways could be followed toward the goal of decarbonization, prioritizing different sets of measures. By applying the same policies altogether (S03) an additional reduction of CO2 emissions is obtained. Compared to S04, policies included in the first three scenarios have less extreme, but still ambitious targets that can ease both their implementation and citizens' acceptance.

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On a Method for Computing Emissions in Freight Transportation

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Abstract. Ecological impact of freight transport is obvious. However, measuring this impact is often limited to assessing CO_2 emissions only. Within this paper, we propose an extension of CO_2 emission computations towards a more general *eco-score* that incorporates other factors like light, particulate matter, or noise. A general outline is presented which steps need to be taken to get towards this more general assessment method. Two examples for a detailed CO_2 emissions calculation as well as a method for light emissions calculations are presented.

Keywords: emissions · eco-score · light · noise · CO_2

1 Introduction

Man-made climate change is real and greenhouse gas emissions are the main reason. In Austria, the mobility sector contributes about 28% to Austria's overall CO_2 emissions—being the second largest contributor behind energy and industries [8]. The Austrian Mobility Master Plan [4] envisages ways to avoid, shift, and improve traffic and transport and follows therewith international visions, cf. [9]. It states that primarily traffic and transport should be avoided whenever possible. Unavoidable transport should be shifted towards more sustainable modes of transport (e.g., rail or inland navigation). And if neither is possible, transport should be improved, e.g., by shifting towards electric mobility. The Austrian master plan for freight transport [3] integrates into this vision and highlights the importance of intermodal transport [1].

The importance of intermodal freight transport is plausible. With respect to CO_2 emissions, rail transport is much more ecologically sustainable than road transport [7]. However, this statement is only partially true. Calculations like these are usually done by estimating the energy need for a specific transport. Depending on the particular energy source, it is then easy to estimate the CO_2

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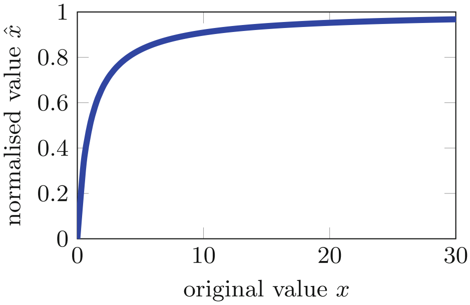

Fig. 1. An exemplary function transforming unbounded values into a $[0, 1]$-range.

emissions. E.g., by first estimating the amount of fuel needed to generated the specific energy (based on the energy density of the fuel) and then calculating the CO_2 emissions for the specific fuel type based on look-up tables. However, even if a vehicle is electric, it is important to account for the primal source of energy. E.g., coal-powered electric trains might be worse than Diesel-powered trains.

Not enough of it, also other types of emissions exist which need to be considered when assessing freight transport. These other types of emissions include, among others, light, noise, and particulate matter. An additional important factor is, for example, traffic safety. Similar considerations have been done for emissions related to ports [6].

Contribution of This Paper. Within this paper, we present a general framework for computing transport related emissions, referred to as *eco-score*, with the following properties:

- The individual emission factors are not of the same unit.
- Weights among the emission factors are not generally known.
- The calculated *eco-score* can be used to objectively compare two possible transports with respect to (overall) emissions.

2 Methodology

Within this section, we highlight key elements of our eco-score and describe how these elements are considered in the actual computational method.

2.1 Unboundedness of Emissions

When accounting for emissions, each gram of CO_2 or each decibel of noise is counting. However, when trying to calculate an eco-score, it is essential that a lower and an upper bound for the values are existing as otherwise a compound value is almost impossible to compute. The lower bound is for all emission types quite easy as it is zero, i.e., there is no emission of that type. The upper bound, however, is not naturally given as it is always possible that there is one additional gram of CO_2 or there is one additional lumen of light. Therefore, we suggest to use the following formula to calculate the normalise value $\hat{x}$ of the actually counted emissions x:

$$\hat{x} = \frac{-1}{(x+1)} + 1 \tag{1}$$

We refer to Fig. 1 for a graphical representation of Function (1) which has the property that it asymptotically approaches the value 1.

2.2 Different Units

As the goal of the eco-score is to compute one meaningful value with respect to emissions, it is essential that all different types of emissions are merged into this one value. For this purpose, it is necessary to "get rid" of all the different units used for measuring the different types of emissions. For example, CO_2 emissions are measured in g while noise is measured in dB. By using Function (1), the values are normalised as they are projected on a value-range of $[0, 1]$.

2.3 Importance of Emissions

While Function (1) can be used to normalise the emission values, this function does not answer one main question. Which of the measured emissions are more important than the other(s). The short answer is: There is no answer. The long answer is: It depends. When assessing different transport modes, it is essential that the desired key performance indicators (KPIs) are defined beforehand. With this definition, the (relative) importance of these KPIs needs to be defined as well. Therefore, we suggest to use the following formula:

$$e = \gamma^{\mathrm{CO_2}} \cdot \hat{x}^{\mathrm{CO_2}} + \gamma^{\mathrm{pm}} \cdot \hat{x}^{\mathrm{pm}} + \gamma^{\mathrm{n}} \cdot \hat{x}^{\mathrm{n}} + \gamma^{\mathrm{l}} \cdot \hat{x}^{\mathrm{l}} + \gamma^{\mathrm{s}} \cdot \hat{x}^{\mathrm{s}}, \tag{2}$$

with γ and $\hat{x}$ denoting the weighting factors and normalised values for CO_2 emissions (CO_2), particulate matter (pm), noise (n), light (l), and traffic safety (s), respectively. The actual values for γ have, however, to be determined by the assessing person.

2.4 Locality of Emissions

In fact, there are two types of emissions. The first one is regional or location-bound. The second one is global. Light emissions or noise emissions (from a transport) are (directly) relevant only in a limited area. Let us give some examples: Noise from a train might wake up a sleeping child whose bedroom is only a few hundred metres from the rail track. A child sleeping in a bed in a different country will not be disturbed by the same train (at the same time). For CO_2 emissions (or greenhouse gas emissions in general) the picture is different. While the CO_2 is emitted locally (at the source of production), its impact is global as it is effective in the atmosphere. Therefore, both children, regardless of their living location, are effected by the same CO_2 emissions. This needs to be considered when calculating impacts. We will provide more details in the following for calculation methods for CO_2 and light emissions.

CO_2 Emissions. As already outlined in Sect. 1, CO_2 emissions can be easily computed for a given transport under the assumption that some basic input variables are known. The more input is available, the more concrete are the calculations. We therefore suggest that for (intermodal) transports, the following set of input data is known:

Route The actual route taken by the vehicle should be known (e.g., specific roads and slopes). This includes, in addition, the speed driven by the vehicle as well as the (intermediate) stops. This information can be estimated (e.g., based on historic data on that specific route) or it can be computed in detail based on GPS-tracks.

Vehicle information on the vehicle used should be available. First of all, which type of vehicle (truck, train, ...). Second, which specific type of truck (or train). Especially, which type of drive-train is used (e.g., Diesel vs. electric). For electric vehicles the source of electricity (and the time/date and location for charging) is essential. Another important source is the actual (net) weight of the vehicle.

Occupancy An important information is the actually loaded weight, i.e., the occupancy of the vehicle.

Transshipments Especially for intermodal transport, the transshipments shall not be disregarded. That is, for each intermediate hub, information on the transshipment technology used (e.g., electric gantry crane vs. Diesel-fueled reach-stacker) and their occupancy is welcomed. Further, if additional shunting operations are necessary, these should be reported.

Even though, it might sound irrational that this information will be available, we highlight that with the EU taxonomy and Corporate Sustainability Due Diligence and amending Directive [2] is is to be expected that this information is mandatory to report soon. Until then, estimates need to be done for missing data, which decreases output quality.

Light Emissions. Light emissions are local. That is, only directly illuminated areas are affected. In Fig. 2, a sketch is presented showing the affected area (shaded blue regions) of a vehicle with a light beam of defined width and breadth. In addition, with respect to impacts on wildlife as well as humans, it is crucial which land-use the affected area has. E.g., if the affected area is residential or nature area the impacts are larger than for industrial areas. Therefore, we suggest the following formula as template

$$x^{\mathrm{l}} = \beta^{\mathrm{r}} \cdot a^{\mathrm{r}} + \beta^{\mathrm{i}} \cdot a^{\mathrm{i}} + \beta^{\mathrm{w}} \cdot a^{\mathrm{w}} + \ldots, \quad (3)$$

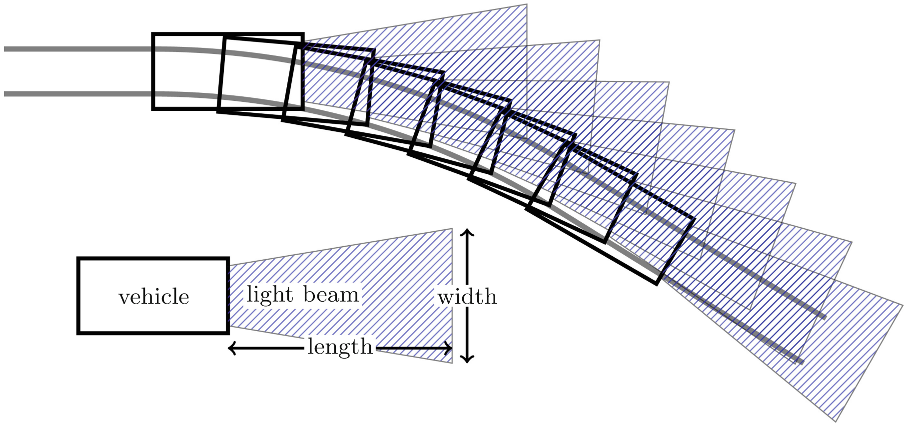

Fig. 2. Sketch of the area affected by light emissions from trains.

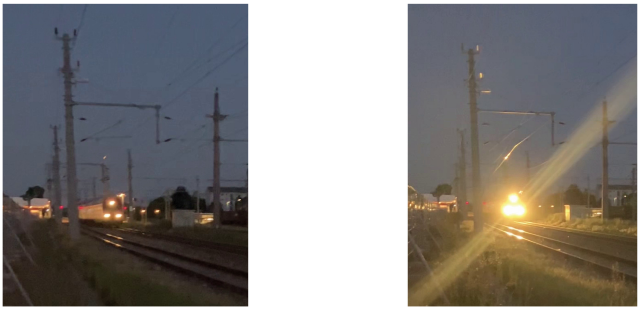

Fig. 3. Exemplary photo shoot of the same train short before (left) and after (right) the high beam has been activated. The dazzling effect is clearly seen. Photo shoot location is approximately 50 m ahead the light source and approximately 8 m alongside the tracks. Source: Authors.

with β and a denoting weighting factors and the affected areas for residential (r), industries (i), wildlife (w), and so on. Obviously, this function is also dependent on the daytime as in the night light emissions are crucial while during day they have no impact (as the sun light is much brighter). To estimate meaningful values for the width and breadth of the light beam, we conducted some preliminary measurements. It turned out that the regularly used trains in Austria's railway network have an effective beam length of approximately 120 m. The breadth is approximately 20 m. We refer to Fig. 3 for an impression of the dazzling effect.

3 Conclusions and Future Work

Within this paper, we presented a novel method for comparing two transports according to their environmental impact. The corresponding norm is referred to as *eco-score* by us. The overall formula has been presented in Equation (2). It is, however, necessary to properly define the weighting factors γ. To get a general set of weighting factors, we suggest to do a broad survey among decision makers asking them for assessing the individual components. However, further input from experts (e.g., physicians, environmental experts, etc.) needs to be incorporated as there have already been investigations on the effects of various environmental influences on (human) health [5]. One of the most important factors is, by the way, noise. This underlines that measuring ecological effects of transports only by computing CO_2 emissions is not enough.

Furthermore, it needs to be discussed whether the eco-score can be further developed towards a more general assessment method by including other KPIs like costs or economic aspects.

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E-Charge: Electrifying Long-Haul Road Freight Transport

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Abstract. E-Charge is a Swedish innovation project gathering fourteen partners representing stakeholders from the industry and academia with the purpose of making an initial system demonstration of battery electric heavy-duty trucks for the long-haul application. The system demonstration to be conducted in E-Charge will be one of the first tests of battery electric trucks for long-haul application on public roads in Europe, utilizing the emerging MCS standard. A first pre-standard edition of MCS (Megawatt Charging System) will be tested within the project, supporting four real logistics flows in southern Sweden during a year's time. Three MCS-chargers will be installed on public locations supporting prototype vehicles from two different vehicle manufacturers. Five PhD students are participating from four Swedish universities and are set to earn licentiate by the end of the project. The main research goal in E-Charge is to identify essential future research areas for the industry and academia within electrification of heavy-duty trucks. E-Charge is partially funded by the public sector through the Swedish research & innovation program for strategical vehicle research and innovation (FFI).

Keywords: Fast DC-charging · heavy duty · long-haul

1 Feasibility Study

Road transport has been identified as one of the main sectors generating CO2 emissions and electrification has been established as one of the adequate technological paths to reducing the sectors emissions. Heavy-duty battery electric trucks are being implemented in urban and regional applications by logistics companies across Europe as several truck OEMs now offer this kind of products to the market. When it comes to long-haul heavy-duty trucks, further technological development and real-life tests and demonstrations are required before commercial implementation.

In 2020, the REEL project (Regional Electrified Logistics) was launched in Sweden with the goal of driving and evaluating four heavy-duty electric trucks for regional application. The project was coordinated by CLOSER at Lindholmen Science Park in collaboration with the Swedish truck manufacturers Scania and Volvo but also including transport buyers and logistics companies DHL, DFDS and DAGAB. In 2021, the project was expanded to a consortium of 45 partners in order to establish and operate prototypes 70 logistics flows all over Sweden with a variety of truck applications and gross weight of

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the vehicle combinations [1]. Both prototypes and serial production vehicles are operated in REEL, showcasing the possibility of electrifying regional logistics flows.

Despite the fact that battery electric trucks for long-haul applications were in an early stage of the development in 2021, the truck OEMs had a common desire to test and demonstrate this kind of vehicles in near future. A consortium consisting of Scania, Volvo, and academic partners from four universities in Sweden was gathered and coordinated by Lindholmen Science Park in a feasibility study to evaluate the idea of testing long-haul battery electric trucks in near term through a system demonstration project. A clear and easily communicated objective for the initial system demonstrator was set. The trucks shall be able to drive for 4,5 h before having to charge. The trucks should then be charged in 45 min during the driver's mandatory break to be able to drive for another 4,5 h. This driving profile requires power levels of up to 1MW, beyond the capability of the CCS standard.

Since two direct competitors were working in the project, the workflow was divided in separate and common activities. Prohibited cooperation between OEMs was avoided since no commercial confident data was shared among partners. The OEMs were able to choose which data from the individual separate activities would be shared to the rest of the consortium. Academic partners were involved in the E-Charge feasibility study through the Swedish Electromobility Centre, a national research center for electromobility. Apart from either confirming or rejecting feasibility of testing battery electric long-haul trucks in a succeeding main project, the industry and academia were able to define areas for future research.

Cooperation between industry and academia indicated a first selection of adequate logistics flows for an initial system demonstrator in the upcoming main project. In addition to the flows, locations for three MCS chargers were jointly examined by the project partners through an analysis of existing truck stops and rest areas for heavy duty traffic in Sweden. It was agreed that the three MCS chargers were not sufficient for a system demonstrator and that additional CCS chargers would need to support the system as well, both at terminals for regular daily charging and along the routes as back-up. It was assumed that public CCS chargers for heavy-duty trucks would soon start to become established across the country. Furthermore, the CCS chargers were commercially available already at the time and thus only limited public funding could be obtained for those in the upcoming main E-Charge project. However, the CCS chargers at terminals were expected to get funding through ongoing government schemes partially financing charging infrastructure, such as Klimatklivet [2].

At the time of feasibility study completion, the partners agreed that the goal of testing battery electric heavy-duty trucks for long-haul application utilizing a combination of MCS and CCS charging was realistic. The feasibility study consortium was expanded with three logistics companies DB Schenker, ICA Sverige, Tommy Nordbergh Åkeri, charging equipment manufacturer ABB, charging point operators Circle K and OKQ8 and the energy company Vattenfall. A project application was sent to FFI - Swedish research & innovation program for strategical vehicle research and innovation - the same funding source as for the feasibility study. Funds for the main E-Charge project were granted in November 2021 [3].

2 Initial System Demonstration

During the initiation phase of the main E-Charge project, one of the primary activities was to define the logistics flows for the system demonstration. In order to gain valuable insights, the project participants agreed on that the logistics flows should be as authentic as possible in terms of weight of goods, logistics nodes and the utilization cycle of the vehicles. Four flows were chosen, concentrated in southern Sweden. Two types of vehicle configurations were chosen as well: tractor + semi-trailer and rigid truck + trailer. The latter is a more common vehicle configuration for road transport in Sweden, utilizing the maximum allowed length of 25.25 m and 4.5 m in height, with a maximum capacity of 48 pallets (96 in two level configuration) compared to 33 pallets in a standard European configuration. Vehicle configurations with a maximum total weight from 40 to 64 tonnes will be driven in E-Charge. The truck OEMs are building two prototype trucks each and are set to deliver these vehicles to the logistics companies in the project during the first quarter of 2024. Temperature controlled groceries, dry groceries, vehicle components and general cargo will be transported in the logistics flows. The system demonstration will be performed during a 12-month period in order to capture various weather, wind, traffic, and other conditions. The daily driving distance is expected to vary between 500 to 1200 km.

Simultaneously, the locations of the planned MCS charging stations were determined. Three stations will be built in three public locations currently serving as fuel service stations for heavy-duty vehicles. In addition, a battery energy storage system (BESS) is planned to be installed at one of the locations due to limitations of the local grid. As this particular charging station will be serving two logistics flows, a rather high utilization rate is expected, roughly 6 h per day during most days. With a small amount of power capacity available and long lead time expected for upgrading the grid capacity, an energy storage was deemed a feasible option providing the opportunity to study the performance of an MCS charger in combination with BESS.

Another workflow performed at the early stages of the project was recruiting PhD students in for the research activities. System research is performed in E-Charge to understand how electrified long-haul logistics system can be implemented with long term benefits both for the transport industry and the society. Five PhD students were attracted to work together yet focusing on individual research areas such as: total system cost, optimal battery sizing, power grid stability, upscaled system charging station location, vehicle energy consumption estimations, integration of electric vehicles to the logistics system and policy development to support the transition towards zero emission trucks. The PhD students are expected to reach licentiate level at the end of the E-charge project. Their individual research will provide an input on future research needs for academia and the industry of several components and subsystems within the overall electrified logistics system.

Lindholmen Science Park coordinates the project and serves as a neutral partner for the interaction between industry, academia, and public actors. The E-Charge project is financed by a research & innovation program for strategical vehicle research and innovation (FFI) managed by the Swedish Energy and Innovation Agencies together with the Swedish Transport Administration. Industry partners are co-financing the project through their participation in the project activities.

2.1 Intermediate Results

As the project is in progress and the logistics flows with the electric trucks and vehicles are yet to be set-up, intermediate project results from the preparation phase are presented at this stage.

During the planning of logistics flows phase an interesting finding regarding current logistics practice was found. Major Swedish logistics companies which are operating flows in a point-to-point network between logistics terminals utilize fast driver swaps (*spetsbyten* in Swedish). According to this set-up, a truck leaving point A is driven towards point B. Instead of the driver taking a break after 4.5 h of driving in the truck, another driver takes over and drives the truck further on towards point B. The original driver takes over another truck heading from B to A, swapping it with yet another driver, arriving from point B, to drive it back to point A. The swap can take place at a service station along a route, a terminal, or an outpost of a logistics company. The set-up challenges the idea of utilizing the mandatory driver break for charging as the vehicle and the driver become separate units. In addition, major logistics companies tend to utilize the trucks for regional distribution during the day and long-haul transport during the night to maximize the number of driven kilometers per vehicle. These fast driver swaps further challenge the set-up as the windows for charging become even narrower and will be examined closely during operation of trucks in the project.

As the MCS-chargers in E-Charge are being installed in public locations, spread over a large geographical area, additional charging is required to serve the initial system demonstration. At the time of writing the application for the main E-Charge project, an assumption was made that by 2023–2024, there would be a few public CCS chargers for trucks along major Swedish roads although the available subsidiaries at the time did not contribute to any significant build-out of public chargers yet. The assumption was based on knowledge of plans of several charge point operators, not least the ones participating in the projects (Circle K and OKQ8), and the knowledge of a major upcoming subsidy for public chargers for heavy-duty vehicles. However, in March 2022, a new governmental scheme, Regional Electrification Pilots (*Regionala Elektrifieringspiloter, REP*), was announced with a 1.4 billion SEK budget for public charging and hydrogen refueling infrastructure for heavy-duty vehicles offering up to 100% financing of investment costs [4]. The scheme finally granted funds for 140 public CCS charging stations and 12 hydrogen refueling stations. A majority of these stations will be in operation in time for the start of the system demonstration in E-Charge. A number of these stations are expected to serve logistics flows in E-Charge which will enable understanding the role of non-MCS charging at lower levels for electrified long-haul logistics flows.

The role of public CCS charging in the system demonstration is mainly to provide backup charging along the route, e.g., when delays occur due to weather and traffic conditions, with the trucks failing to reach an MCS-charger. In addition, charging is required at the logistics nodes since the vehicle will have the performance of being able to drive for 4.5 h corresponding to maximum continuous driving time for European drivers. With the MCS chargers located roughly in the middle of the project routes, the trucks will be arriving to their destination points with rather low state of charge (SoC). As stated above, trucks may have quite short turnover times at the logistics nodes which increases the need of high-power charging there as well. Securing necessary grid capacity may be quite challenging at logistics terminals as was previously found in the REEL project although only trucks for urban and regional applications are operated in REEL [5]. The shorter turnover times are also putting emphasis on the reliability of charging equipment and resilience of the energy system at a logistics terminal. Long-haul and line-haul trucks tend to spend short amount of time and reload at logistics terminals during the times of day when the overall energy and power demand in the society is at its highest thus requiring high power charging when the power capacity is utilized the most. With little to no time for charging at low power levels, long-haul trucks may become a significant challenge for logistics terminals generating demand for BESS and/or changes in the logistics setup in order to achieve peak shaving [6].

At this initial stage, the trucks will be equipped with both CCS and MCS inlets which may require additional software to enable switching between the two types of charging in the vehicle. As the MCS-standard is not yet set, changes to the standard may still occur. Recently, a communication standard for MCS has been altered by the standardization organization CharIN. Power-line Communication (PLC) was replaced by Ethernet to provide for a more stable communication between the vehicle and the MCS charger. This will delay the system demonstration in E-Charge as the consortium decided to utilize Ethernet as well. Other transport related equipment such as trailers are also expected to be electrified too. Currently, cooling units are being powered by diesel generators contributing to noise and emissions. With the emergence of electrically powered cooling units and generating and/or electrically driven axles of the trailers, charging of trailers may become a necessity as well. Additional questions in terms of charging standard for trailers as well as layout of future charging locations arise.

Apart from preparing for the initial system demonstration and performing the research activities in E-Charge, a potential future expansion of the project is examined together with project participants. The primary method for this workflow is through interviews conducted by the coordinating part Lindholmen Science Park that also functions as a trustee. Primarily, the purpose of this workflow to investigate the necessity of a larger system demonstration and its potential content. Another purpose of the interview study is to examine the project participants views regarding the requirements for how the authorities should facilitate and plan for charging infrastructure for heavy duty battery electric trucks. Since the project gathers pioneers in electrification of the long-haul road transportation, the Swedish Transport Administration and Swedish.

Energy Agency expressed their interest in results of the interview study. Input from project participants was gathered during 2023 and shared to the agencies after being subjected to data filtering by Lindholmen Science Park. This input has been incorporated during the agencies common work on a governmental assignment to prepare for an action plan on national charging and hydrogen refueling infrastructure [7].

At the TRA 2024, the project representatives aim to present preliminary results from the system demonstration which is expected to have been in operation for several months.

The E-Charge project, as the preceding feasibility study, is financed by a research & innovation program for strategical vehicle research and innovation (FFI) managed by the Swedish Energy and Innovation Agencies together with the Swedish Transport Administration. Industry partners are co-financing the project through their participation in the project activities.

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Assessment of an Integrated Cooling/HVAC Circuit for Electric Heavy Quadricycles

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Abstract. Within the last decades, an always increasing attention has been addressed to the development and market diffusion of alternative powertrains, either hybrid or fully electric. Especially for electric powertrains some open points are nowadays still present with respect to thermal management and cabin comfort, which are intended to be addressed in the present study. This is the reason why the European Commission is striving the research towards the development of innovative and efficient electric powertrains. Within this framework, the REFLECTIVE project aims at developing an electric heavy quadricycle equipped with a HVAC module integrated with the powertrain/charging cooling system, with the aim of reusing part of the heat generated at the powertrain during driving conditions to heat up the cabin, with the consequence of reducing the thermal power requested at the electric cabin heater to fulfil this task. Although an additional heat exchanger is required, it is possible to guarantee a certain amount of heat preventing the use of the battery for the electrical heater activation. Moreover, the battery thermal management as well can be done also using hot/fresh air generated by the HVAC sub-system. By this way, several thermal loads can be managed through the same integrated circuit with apparent benefit in terms of energetic efficiency, despite some complexity is introduced. The aim of this paper is to assess the effectiveness of this solution on the vehicle range and battery state of charge, through the integration of a 1-D model of the cooling circuit with a 0-D model of the entire vehicle. Different driving conditions, namely summer and winter scenarios and different speed profiles, will be considered. Results show that the HVAC and cooling systems have a huge effect on range reduction with respect to the range estimated, but at the same time, but the benefit of the recuperator can be also assessed.

Keywords: heavy quadricycle · cooling circuit · air conditioning · energy efficiency · thermal management

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1 Introduction

The presented work falls into the activities carried out within the REFLECTIVE H2020 EU project [1], presented in [2], and deals with the assessment of an innovative integrated cooling/HVAC system for the light electric vehicle under development. In particular, with the aim of improving the energy efficiency of the overall system and reduce the number of powertrain components, the battery and HVAC thermal managements are deeply integrated in order to contemporary ensure occupants' comfort and battery optimal operation and durability. In this pursuit, the HVAC is primarily used to assure the proper operating temperature at battery side, by directly sending conditioned air either from the HVAC module or from the cabin to the battery unit, and, at the same time, to guarantee comfort into the cabin itself. More specifically, the battery case considered in this project is not equipped with internal heaters. Thus, both the cooling and heating processes have been directly managed through the HVAC module itself. However, for heating purposes, as soon as the battery reaches a safe operation temperature (i.e. 15 °C), warm conditioned air into the cabin can be used for battery heating purposes, this will help the cabin comfort without significant penalization at battery TM. In fact, the performance and lifetime of lithium-ion batteries, which have been chosen for the prototype under development due to their high electrical energy density, are particularly affected by cold starting as well as heat generation during cyclic charge and discharge processes, occurring during a vehicle mission. This asks for a carefully balanced thermal management to keep their operating temperature in an appropriate range, i.e.15–40 °C, [3], also related to safety needs, as it almost eliminates potential hazards associated with uncontrolled temperatures or thermal runaway [4].

Obtained results are twofold. On one hand, during winter driving scenario, the presence of the recuperator allows saving a sensible amount of energy, with assuring optimal battery operating temperatures and comfort at vehicle's occupants, although some driving range penalizations are introduced by the usage of an electric heater. On the other hand, during summer scenario, there are no possibilities to recover useful heat, and the energy consumption requested by the HVAC compressor, both for battery and cabin temperature control, can hardly penalize the driving range.

2 Cooling Circuit Description

The methodology behind the cooling circuit design has been already presented in [5] and led to the layout proposed in Fig. 1. For sake of fluency, only the most interesting features of the layout are again explained here. As a first note, in the pursuit of the main idea of coupling the battery TM to the HVAC system, specific ducts are used to direct part of the hot air present in the cabin to the battery case, to heat it up when the battery reaches a safety temperature threshold (here 15 °C), while other ducts are employed to partialize the cold/hot air from the HVAC, sending part of it to the battery to cool/heat it down/up, at really hot/cold battery conditions, and the remaining part to the cabin for conditioning purposes. Thus, both during winter and summer driving scenarios some side effects on the cabin occupants' comfort can be observed. During battery cooling/heating the reduction of the cold air mass flow rate entering the cabin slows down the cabin cooling/heating processes, due to the higher priority of the battery TM realized at the expenses of occupants' comfort. Moreover, since in pure electric vehicles waste heat sources are less significant than in internal combustion engine ones, a dedicated electric heater (PTC in Fig. 1) is added to the circuit to allow for cabin heating during winter, albeit the presence of a Recuperator (red and blue rectangle in Fig. 1) employed to recover the available heat at the powertrain output. In particular, the hot coolant at the inverter/e-motor outlet is sent to this component to pre-heat the liquid before passing through the PTC branch, with the aim of reducing its load to preserve battery charge. Moreover, this heat exchanger helps the main Radiator in the reduction of the e-motor outlet coolant temperature, thus reducing the number of occurrences of radiator fan activation, resulting very beneficial in terms of energy consumption. As per the main radiator, another interesting aspect of the proposed layout is the radiator bypass, activated during warmups to speed up the thermal transients, by reducing the active heat transfer surface.

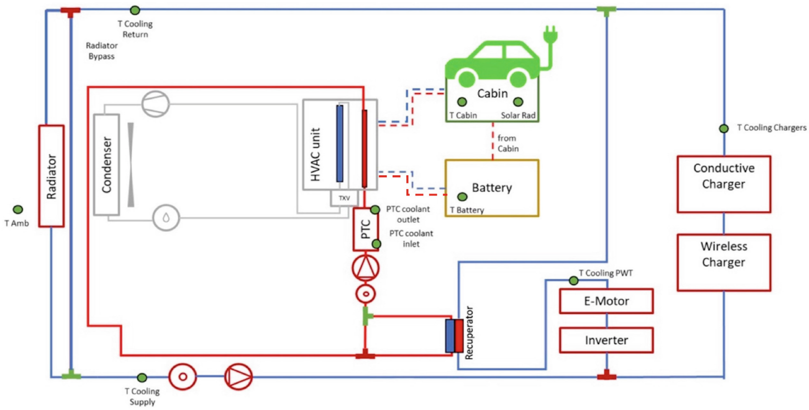

Fig. 1. Combined layout configuration for REFLECTIVE cooling/HVAC systems.

3 Modelling Approach

In order to properly evaluate the heat rejections of the powertrain components, namely e-motor, inverter and battery and to assess the effect of the HVAC loads on the vehicle range and state of charge trajectory, a self-made a quasi-static forward-looking simulator of the entire vehicle, developed in Matlab/Simulink, is used [6]. In this simulator, the driver is modeled as a PID controller, that tracks a desired vehicle speed trace; the e-motor is modeled by means of a stationary efficiency map and maximum/minimum torque curves, the battery is modeled through a 0-th equivalent electric circuit model, while the inverter is modeled as a constant conversion efficiency ($\eta_{INV} = 98\%$). The effective vehicle speed is instead computed by solving the longitudinal vehicle dynamics equation. The inverter instantaneous power losses $\dot{Q}_{INV}$ are estimated as a function of the inverter power P_{INV} through the following:

$$\dot{Q}_{INV} = P_{INV}(1 - \eta_{INV}) \quad (1)$$

The instantaneous power losses of the e-machine $\dot{Q}_{EM}$ are:

$$\dot{Q}_{EM} = |P_{EM}|(1 - \eta_{EM}) \quad (2)$$

where $|P_{EM}|$ is the absolute value of the power request to the motor (which can be positive in traction and negative in braking), and η_{EM} the instantaneous efficiency of the electric machine and is estimated through a stationary map as a function of instantaneous torque and rotational speed (shown in [5]). Finally, the thermal load of the battery is thus computed as a pure resistive ohmic loss:

$$\dot{Q}_{batt} = I^2 R_o \quad (3)$$

where I is the current flowing through the battery and R_0 is the internal resistance (SONY-US18650G3 [7]). The vehicle under analysis is a L7e-C heavy quadricycle, with a curb weight of 600 kg without the battery pack, in respect of the EU Regulation No 168/2013. A drag coefficient of 0.3 and a vehicle frontal area of 2.17 m^2 have been used, while the rolling resistance coefficient considers a tire pressure of 2 bars.

Simulations have been performed for a real-like driving cycle of the city of Helsinki and for the standard Revised WMTC, which is the prescribed test cycle for Euro 5 compliant L7e-C heavy quadri-mobiles [8].

The Helsinki cycle is characterized by an initial extraurban-like part of roughly 38 min, that allows reaching a maximum speed of 90 km/h, as per the vehicle class homologation constraint, and a second urban-like part of around 60 min with a maximum speed of 45 km/h.

4 Results and Discussion

In this section, the results will be shown in terms of driving range and SoC trends under different operating conditions. The developed control logic has been already verified in [5], thus, for sake of brevity, no particular details will be reported in this paper. Nevertheless, in the present analysis, the influence of the integrated cooling/conditioning circuit on the vehicle range and state of charge trajectory are assessed with considering different scenarios. More in detail, winter and summer seasons have been simulated, according to their specific ambient conditions (starting components' temperature of about 0 °C vs 40 °C); while three different loads from auxiliaries have been included: no load, load only for battery TM (Cabin OFF) and load for battery TM and cabin comfort (Cabin ON), respectively. Obviously, for all the scenarios, for sake of completeness and reliability, the load due to the cooling circuit has been always included. Results, in terms of driving range for all the considered operating conditions, have been synthetically reported in the next Table 1.

With respect to Table 1, one can easily observe how the presence of a conditioning system significantly penalizes the vehicle driving range. In fact, while the auxiliaries have been used both for battery and cabin TM, the driving range has been drastically reduced, especially during summer season. On the contrary, during winter driving, one can observe the positive impact of the recuperator which allows some energy savings through taming the request at electric heater. This can be read in terms of driving ranges, too, which are always higher during winter with respect to summer. Moreover, it can be pointed out how the cabin conditioning drastically impacts the vehicle driving range, with really penalized results at WMTC summer, where the final distance is reduced of about 75% (30.51 km vs 131.10 km).

Table 1. Vehicle range for different driving scenarios and load conditions.

Range [km]			
Scenario	NO Load	Cabin ON	Cabin OFF
Helsinki Winter	95.30	70.98	82.86
Helsinki Summer	95.30	43.58	66.51
WMTC Winter	131.10	67.44	101.68
WMTC Summer	131.10	30.51	71.27

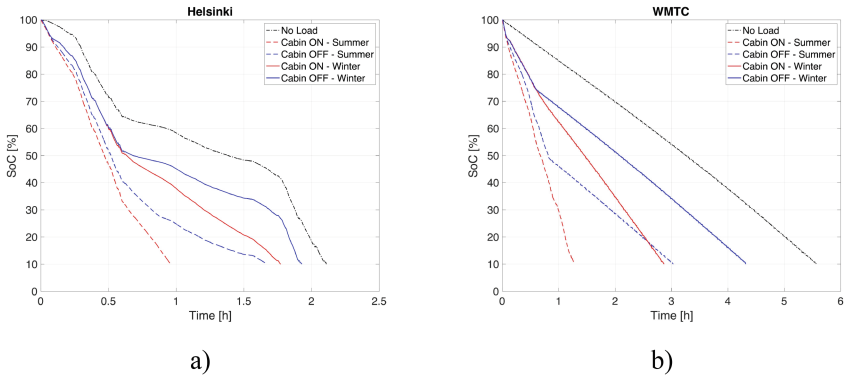

Fig. 2. SoC for different operating conditions: a) Helsinki, b) WMTC.

Figure 2 clearly shows how the presence of the battery thermal management, as well as of the HVAC, significantly modifies the slope of the battery state of charge during time. More specifically, during the first phases of the discharge, all the curves present a steep slope due to the high energy requirement for battery thermal management, while the slope gets smoother whenever the cabin HVAC is switched off (Cabin OFF). Again, one can observe how the summer scenario is the most demanding condition from a SoC perspective, as well. More quantitively, Fig. 2b apparently depicts how the two blue curves (Cabin OFF) present a SoC slope reduction as the HVAC is switched off, while the red ones (Cabin ON) do not show any change in SoC slope, with drastic reduction of driving range. Similarly, the effectiveness of the recuperator is again confirmed, while the influence of cabin heating can be appreciated even in this occurrence, with reduced ranges whenever the HVAC is used for comfort purposes as well.

5 Conclusions

This paper has shown the capabilities of the integrated control strategy developed within the execution of REFLECTIVE project. Results have clearly highlighted the influence of HVAC systems in EVs both for battery TM and cabin comfort. The high demanding consumption from such a kind of components, in comparison with the e-motor power, is asking for a development and adoption of an innovative system, such as heat pumps. However, the availability of off-the-shelf components have striven the choice towards traditional component, within a framework of an EU project aimed at developing a fully functioning vehicle, ready for crash tests and homologation.

Nomenclature

EV	Electric Vehicle
HVAC	Heating Ventilation Air Conditioning
PID	Proportional Integrative Derivative
PTC	Positive Temperature Coefficient heater
SoC	State of Charge
TM	Thermal Management
WMTC	World Motorcycle Test Cycle

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New Attractiveness of Rolling Stock: Circular and Modular Interiors

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Abstract. According to 2021 Circularity Gap Report, global GHG emissions could be reduced by 39% with a circular economy. Rail transport is one of the most sustainable means of transport. However, trains consume material resources for their manufacturing and maintenance.

Current trains are not fully designed for modularity and for circular economy, and need to be kept attractive during their 40 years lifetime. The interiors are based on a tailor-made design specific to each series and customers, and quick-fit fasteners are almost not existing, which limits the range of reusable solutions. It also increases purchasing and replacement costs. The project Attractiveness is integrated in the European Research Program Rail4EARTH and it received fundings from the European Union's Horizon Europe research and innovation program under grant agreement No: 101101917. The purpose is to strengthen train attractiveness by facilitating modal transfer and by making train more circular.

The project is split in two main topics:

- Sustainable interiors focus on innovative modular and circular interiors
- User experience and user interface focus on new architectures and new human interfaces

Each topic is built in three main steps: knowledges, concepts, and demonstrators with the objective to offer several mock-ups scale one as the final deliverable Phase 1 in 2026.

Keywords: Circularity · Modularity · Attractiveness

1 State of the Art

The sate-of-the-art offers the partners the opportunity to share knowledges, to open up inspiration and to gather data to create design references.

1.1 Sustainable Interiors

Sustainability in railways comes with interiors dedicated to current passenger needs to increase modal transfer. Today, train layouts are defined once and for all at the start of

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the design phase and several years go by between the beginning of the project and the train putting into service. Which means, the interior layout is already quite outdated in terms of passenger expectations. For example, the recent massive increasing demand of bicycles on board could not be integrated during the design phase of most of trains currently in commercial operation.

One answer to this problem is modularity. By providing a quick and easy way of modifying interior layout, modularity allows operators to adapt interior more frequently which improves passenger service and railway's market share among other transport.

Modularity can be motivated by:

- The ability to adjust between off-peak and peak hours (more standing space to improve capacity during peak hours)
- The ability to adjust between seasons (workweeks vs holidays/weekends)
- New functionalities/technologies improving sustainability and/or passenger experience

The first step before starting any research program is to analyse the state of the art and understand on which points, we should focus to be the most efficient.

All participants started with a 5Why's exercise to find out the root causes of the current lack of modularity. The following key factors have been identified:

- the lack of standardization of the interfaces between train and interiors
- the high level of perceived quality required
- the high level of personalization required
- the high mechanical stress on fastening solutions

Interior fittings (seats, tables, luggage racks, …) are mainly fixed to the car body shell directly. Standardised interfaces would speed up the design of interior parts as some parts could be reusable, or interior design could begin at the same time as the body design, rather than afterwards.

Participants were asked to go deeper into the study of interfaces. It was shown that the key drivers of interfaces heights are car body shell gauge, customers and structural requirements.

As well as showing that the heights of the interfaces were not standardised, even if they came from the same manufacturer with a similar train architectural design, the state-of-the-art study pointed out the wide variety of fasteners used for interiors, the lack of standard parts shared between interior modules and the current time taken to change a car layout.

Those preliminary study phases helped us to determinate the technical challenges we would face in the next steps:

- Provide as much as possible standard interior interfaces while the variable car bodyshell gauge influence their position and/or angle.
- Limit the weight increase due to continuous interfaces instead of predefined located ones
- Keep a high level of personalization while standardizing to a maximum building blocks
- Keep a high level of perceived quality while reducing the time to change the layout

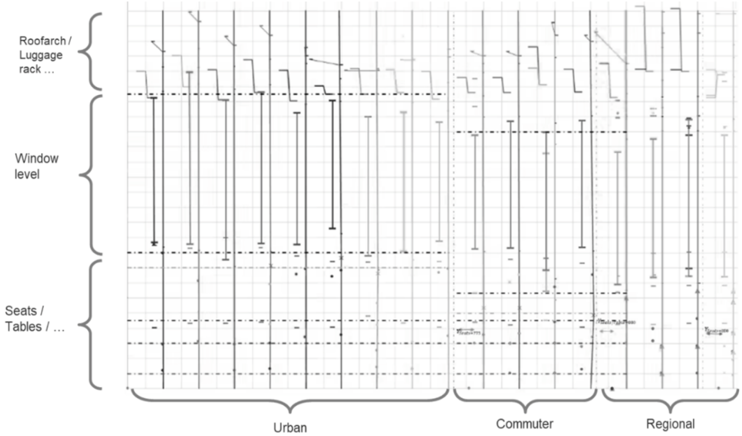

Fig. 1. The diversity of interfaces heights in several rolling stocks from different train architectural designs

1.2 User Experience and User Interface

From the result of the European project Roll2Rail No. H2020 – 636032 "WP6 Comfortable and Attractive Train Interiors" which public surveys in Europe and survey done by the members (France, Germany, Italy, Spain and UK, 2016–2019), cleanliness is one of the five decisive criteria to increase the attractiveness of railway compared to other transportations. The current solutions are costly and very linked to human action, ideally on board during the travel. On the other hand, the interior design is not entirely designed for cleanliness or for hygienic performance in the choices of materials, shapes or assemblies.

Two ways have been identified to increase the quality perceived without increasing the maintenance cost: one is about limiting the need to touch controls with testing and evaluate the benefits of touchless technologies, the other one is about the materials and how to assemble them to facilitate the action to cleans and limit the dirt and grime (Fig. 2).

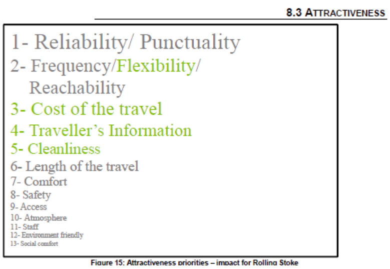

Fig. 2. Attractiveness – impact for Rollingstock (extract of Roll2Rail Deliverable D6.3)

With toilets, seats are one of the costliest equipment of the interiors, almost 50% of the cost of the interior's refurbishment. It is also the equipment the most in contact with passengers.

During the state of the art, we have identified the same issue between operators: the latest markets shown that refurbish an old seat is more costly compared to product and integrate a new one.

Seats are technically designed to resist 40 years and easy to repair but they are not designed to evolve in terms of comfort or service or to keep pace with changing needs. Trains are optimized for maintenance, production, and maximum lifecycle without refurbishment.

2 Biomimicry as a Method of Innovative Proposals

In search of circular and modular train designs, biomimicry offers a valuable approach. Biomimicry is a growing field that takes nature as a model, mentor and measure for sustainable, even regenerative innovation. It is based on the premise that (the rest of) nature has already built up 3.8 billion years of evolutionary knowledge, and we can emulate and mimic its forms, processes and systems to solve societal challenges. An important factor that sets biomimicry apart from bio-inspired design is that it aims to create designs that function like nature. Besides a design tool, biomimicry is also a philosophy, aiming to design in a way that creates conditions conducive to (all) life on Earth - without overshooting its planetary boundaries, and to deepen our relationship with nature.

2.1 Design Approach

The biomimicry practice follows a highly iterative design process, applicable to any kind of design challenge. Roughly, there are four stages in the 'Challenge to Biology' approach to achieve a biomimicry solution:

- Scoping, where the context of the design challenge is defined, as well as the function(s) the design solution must have in order to be successful.
- Discovering, where natural models that address the same functions and context as the design solution are explored, and their strategies are studied.
- Creating, where natural strategies are abstracted into principles that can be applied to the design solution, and;
- Evaluating, where the design solution is measured against the criteria and constraints of the design challenge.

2.2 Application in the Project

Studying how nature builds with minimal use of materials, while maximizing design effectiveness and strength, can guide the design of train interiors with lower material costs. Furthermore, nature transitions materials in continuous loops, and designs optimally with available resources to avoid unnecessary waste, paving the way for circular train designs. Additionally, a more comfortable travel experience can be offered by maximizing space and hygiene in innovative ways.

All participants took part in a biomimicry workshop to get familiar with this process.

As part of the scoping phase, different design challenges linked to each work package were defined, as well as the function(s) linked to each challenge. A preliminary literature study on the possibilities of biomimicry for circular and modular train interiors revealed the biomimicry potential of each challenge. The challenges with the highest biomimicry potential are input for the following research phase (see Fig. 1).

WP	Challenge
24	Create circular seating
24	Create lateral and ceiling structures with biobased/renewable materials
24	Create circular flooring with biobased/renewable materials
24	Adapt lay-out to seasonal demands (e.g. for bikes)
26	Improve hygiene by reducing smells and preventing graffiti adhesion
26	Maximize the number of train passengers

Fig. 3. The challenges identified during the first step of the project

3 User Experience on Board

Seat and toilet are two key factors of customer experience on board. In a train, more than 90% of the time is spending in the seat, and an hygienic design, especially for toilet, is a crucial passenger's expectation. The project will be focused on these two topics to complement the workpackages dedicated to Sustainable interiors (Fig. 3).

3.1 Seats

The seats are one of the components most interested by the passengers because they represent the comfort and the design of a train. For this reason, our focus on seats is dedicated to enhance the comfort and the usability of this component with a special attention to the sustainability and the circularity of each part by using natural materials. But also with the objectives to develop those features that can transform a day travel into a relaxing experience and a step towards a more sustainable future.

The use of new materials for the upholstery, for the padding or for the shell, can be useful to update the project in order to achieve benefits in terms of environmental impact, recyclability and ease of maintenance.

Others special attentions must be paid to ease of cleaning, to maintain a safe environment/atmosphere when travelling for study, work or holidays.

The opportunity to reduce the weight of train components is also in the direction of CO2 footprint.

3.2 Toilets

Toilet is the main service on board expected just after passenger's information and it should improve the issue of quality perceived with challenging the hygienic performance even in a mass transit transportation and technical issue with offering the capability to install or remove a toilet easily during the life of train to follow the operation's need of a line.

Nota: the traveler's information is one of the major item of passengers experience, but it is a specific digital topic developed in other sub-projects of ERJU Program more transversal.

4 Results Expected in 2024

For Sustainable interiors, the results of research aimed at minimising the need to produce new materials by maximising the reuse of resources over the life cycle include several trains and several operators.

The first pre-concepts of interiors will be presented: design principles inspired by biomimicry and "low-tech" approach for a full "plug and play" interior design that will facilitate the reuse between trains.

For User experience and user interface, the results of research aimed at opening the main technical locks by adapting the train to customer demand and by developing modular architecture and products: The main focus will be about seats and toilets. The first pre-concepts for installing toilets anywhere and new modular seating to expand or adapt services. Also, principle design are inspired by biomimicry for a full hygienic interiors design adapted to mass-transit.

The main schedule of the project:

Spring and Summer 2023 State of the art/Autumn 2023 Opportunities/Winter and Spring 2024 – ideation/Summer and Autumn 2024 – concepts/Winter to Autumn 2025 – pre-studies.

Technico-Economic Feasibility Study of On-Board H_2 Production in a Passenger Hydrogen Train for Railway Operators

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Abstract. This study aims at assessing the technico-economic feasibility of on-board hydrogen production for train operations with the objective to eliminate the need of hydrogen refuelling infrastructures. The concept is technically feasible considering the performance of hydrogen technologies, provided R&D investments for on-board electrolysers. The economic advantage or drawback depends mainly on the future costs of H_2 production and electricity prices.

Keywords: hydrogen trains · technico-economic feasibility · railway operations

1 Introduction

1.1 Context

The French national operator SNCF has an objective to reach carbon neutrality by 2050. Today, even if the rail transport is a low carbon emission activity, 20% of rail operations are carried out using fossil fuels on non or partially electrified lines. Solutions such as increasing the electrified portions or introducing hybrid trains, battery trains, biofuel trains or even hydrogen trains into operation are under deployment. Hydrogen trains appear as a relevant solution, like the bi-mode Régiolis H2 soon under tests, but present operational and economic locks. Whether in terms of the autonomy of the train or in terms of the expensive hydrogen infrastructure, the H_2 does not currently meet all expectations. Hence the idea is to produce hydrogen on board the train when operating under catenaries or at depot (reversible hydrogen train), in order to increase the autonomy and avoid costly hydrogen infrastructure.

The objective of the paper is to determine whether a reversible hydrogen train concept would not only be technically feasible but could meet operational constraints while avoiding the construction of hydrogen infrastructure.

1.2 State-of-the-Art

To date, almost no hydrogen train is commercially operated, except the ALSTOM Coradia iLint, a single mode train in operation on regional lines in Germany [1]. The literature

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on the subject begins to be rich but only with regard to the operation of a classical dual-mode vehicle [2], like the Régiolis H2, and the examination of the production solution in electrolysis on the ground [3]. Thus, the reflection on the operation of a reversible dual-mode hydrogen train has clearly not yet been addressed by the scientific and industrial community.

2 Hypotheses and Methodology

The study is divided into two parts.

The first part consists in sizing the hydrogen consumption and production systems within the train, while ensuring train availability.

The second part consists in carrying out an economic analysis of this train concept by studying the costs of the reversible hydrogen train and on the other side of the Régiolis H2 hydrogen train, to estimate the most cost-effective solution in each situation.

2.1 Preliminary Sizing and Analysis of the Availability of H2 Reversible Train

The first step was a preliminary design of the H2 reversible train using a simulation tool to ensure that the components integrated in this train allow it to operate on a constraining daily journey [4]. The components were chosen for their performances and size and weight, following a study and technological forecasting of hydrogen technologies which proved preliminary feasibility of the concept [5].

The simulation tool (schematized in Fig. 1), created for this purpose, simulates the train's behaviour depending on on-board components, available hydrogen stocks, energy management carried out by the train, and data, supplied by SNCF, indicating the train's energy requirements at each point of the daily journey studied. The model developed gave precisions around 5 to 15%, and 83% of the cases were overestimated, which means results are coherent and give already margin for the dimensioning.

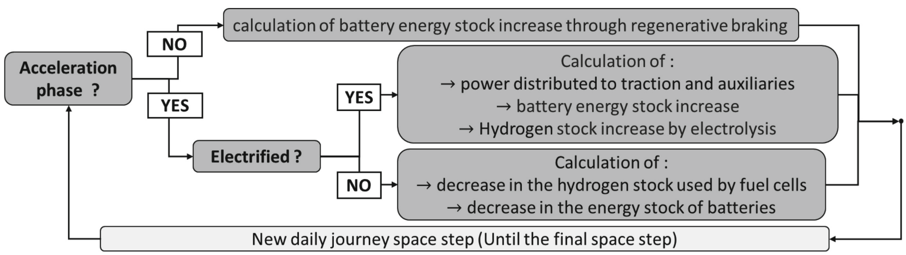

Fig. 1. Program block diagram

The characteristics given in the table below correspond to an Auvergne-Rhone-Alpes (AuRA) daily route, making round trips between Clermont Ferrand and Lyon. It has been selected to be a challenging daily journey with data studied in the context of Régiolis H2 operation (Table 1).

Table 1. Auvergne-Rhône-Alpes (AuRA) daily journey characteristics

Total length	Electrified length	Non-electrified length	Length to be electrified for allowing Régiolis H2 operation
900 km	335 km	565 km	8 km

The second step is the verification of this train availability.

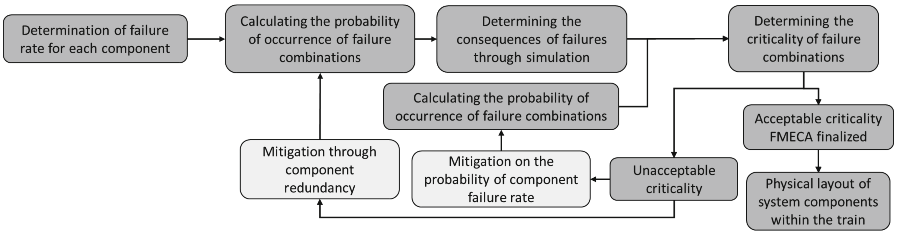

Fig. 2. Schematic methodology to ensure the system availability.

As shown in Fig. 2, the preliminary step in ensuring the availability of the dimensioned H2 reversible train is to determine the failure rate of each system component.

Failure probabilities for each component, obtained through literature searches [6, 7, 8, 9, 10] and cross-referencing of datas, are shown in the table below (Table 2).

Table 2. Failure rate of on-board components

Component	PEM fuel cell	Tank	Compressor	Electrolysers
Failure rate	$5{,}66.10^{-4}/h$	$3{,}10.10^{-6}/h$	$4{,}10.10^{-3}/h$	$9{,}5.10^{-5}/h$

The next step is to calculate the probability of occurrence of each admissible failure combination, and then simulate their impact on train availability thanks to the simulation tool (Fig. 1). Based on the probability of occurrence of the various failures and their effect on the train's availability, the criticality of each failure combination can be judged as acceptable or unacceptable following the standard SAM005 for train braking and used by the industry for hydrogen applications.

In cases where the criticality of a combination of failures is deemed unacceptable, it is necessary to perform mitigations, by having redundancy on certain components, or by specifying a target failure probability to comply with. The probability of occurrence calculations is then repeated, and the impact of the associated failures is simulated once again, to determine whether the mitigations carried out have been sufficient to accept the criticality.

If the criticality of each failure is deemed acceptable, the next step is to determine the layout of the elements, in terms of their dimensions and the links between them, within the dedicated space of the train.

2.2 Cost Comparison Between the Hydrogen Train and the Reversible Hydrogen Train

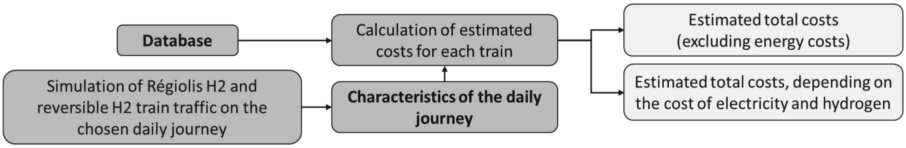

Fig. 3. Schematic methodology to estimate the costs of H2 reversible train and Régiolis H2

The aim of the cost analyses carried out is to estimate the total costs of the reversible hydrogen train and the Régiolis H2, for an operating period of 20 years which is the half-life of a train i.e. when it will be retrofitted, and for a given number of trains operated on the daily journey studied. Total costs include investment costs for on-board components and additional infrastructure (CAPEX), replacement and maintenance costs for the various components and infrastructure, and train energy costs (OPEX) (Fig. 3).

The preliminary step in this economic analysis is the creation of a database listing the CAPEX costs of each on-board component and infrastructure, obtained from orders of magnitude from SNCF, required to operate each train on the daily journey. For each component and infrastructure considered, the database also includes information on maintenance costs, that are a percentage of CAPEX widely used in the industry, and service life, so that replacement frequency can be estimated.

Thanks to the simulation tool (Fig. 1), it is possible to obtain information on the length of track to be electrified and the need for additional electrical substations on a specific line, both for the Régiolis H2 and for the reversible train operation.

Based on the number of trains operated, the number of hydrogens refuelling stations for Régiolis H2 were deduced. The need to electrify or not the depot for the reversible train is also an important parameter.

As energy costs (electricity and hydrogen) are highly variable and difficult to estimate over 20 years, they appear as variables in the results.

3 Results and Analyses

The hydrogen system to be carried on board the train, including fuel cells, tanks, compressors [11], and electrolysers [12] for the on-board hydrogen production, requires too much volume for available space. The solution was therefore to create a dedicated car for this hydrogen system that could be arranged as in Fig. 4.

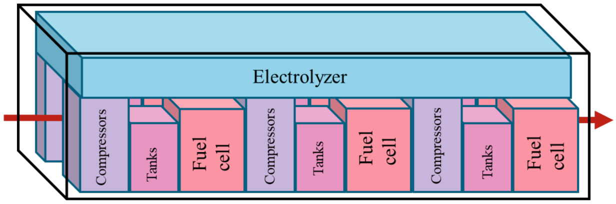

Fig. 4. Hydrogen dedicated car configuration diagram (Dimension: 13.8 m – 2.85 m – 4.29 m)

The probability of failure of the electrolyser must be at most $9{,}5.10^{-5}/h$ and its volume less than 67,7 m^3. If these specifications are not met, the train would present availability problems deemed unacceptable by the FMECA or feasibility criticality.

During the cost analyses, various parameters were identified as having a particular impact on the total costs. The most impactful parameters are (Table 3):

Table 3. Parameters with a significant impact on total train costs (CAPEX + OPEX)

Cost of on-board electrolysers
Energy costs per train
Additional substations and length of electrification required to operate each train
Need of fast static charging infrastructure in depot to provide electricity to H2 reversible train to produce hydrogen by electrolysis

The reversible hydrogen train is more cost-effective than the Régiolis H2 in the following cases:

When the number of substations or the number of additional kilometers required for the Régiolis H2 is high.
When the number of trains operating is as low as possible.
When train depots are already electrified with 25,000V AC and equipped with static recharging facilities.

The table below gives an example of the cost (CAPEX + OPEX) comparison between the reversible hydrogen train and the Régiolis H2 train on AuRA line, assuming the depot is already electrified. The green boxes indicate when the reversible hydrogen train is more profitable than the Régiolis H2 (Table 4).

Table 4. Total cost in millions of euros, for 5 trains in operation over 20 years on AuRA, for the reversible hydrogen train and the Régiolis H2

		Reversible H2	Régiolis H2	Reversible H2	Régiolis H2	Reversible H2	Régiolis H2	Reversible H2	Régiolis H2	Reversible H2	Régiolis H2
Cost of hydrogen production for fleet and 20 years [€/kg]	1.5	169,1	179,6	189,7	184,9	210,3	190,2	230,9	195,5	251,5	200,8
	3	169,1	188,9	189,7	194,2	210,3	199,5	230,9	204,8	251,5	210,1
	4.5	169,1	198,3	189,7	203,5	210,3	208,8	230,9	214,1	251,5	219,4
	6	169,1	207,6	189,7	212,9	210,3	218,1	230,9	223,4	251,5	228,7
	7.5	169,1	216,9	189,7	222,2	210,3	227,5	230,9	232,7	251,5	238,0
	9	169,1	226,2	189,7	231,5	210,3	236,8	230,9	242,1	251,5	247,3
	10.5	169,1	235,5	189,7	240,8	210,3	246,1	230,9	251,4	251,5	256,7
		50		**100**		**150**		**200**		**250**	
		Electricity purchase cost [€/MWh]									

4 Conclusions and Perspectives

This study sized and established the feasibility of a hydrogen train with on-board hydrogen production system. Thanks to the addition of a dedicated car, the train concept imagined in this paper would be able to eliminate the need for a hydrogen refuelling station, using only electrical energy for its operation and refuelling its hydrogen tanks.

This train concept would also avoid the complex logistics involved in hydrogen production and distribution.

In economic terms, the profitability of the reversible hydrogen train depends on several factors, such as the electrification and addition of substations required to operate the Régiolis H2, the need to add a static recharging infrastructure for the reversible hydrogen train, the number of trains operating on the daily journey, and the costs of hydrogen and electricity.

However the economics saving might not be important enough to finance the required R&D to embedded an electrolyser and its auxiliaries. More studies need to be carried out like the economic impact at network level, a comparison with a train with an additional battery car, a more precise feasibility study of on-board electrolysers and ROI estimates.

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Lowering Transport Environmental Impact Along the Whole Life Cycle of the Future Transport Infrastructure: LIAISON

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Abstract. Liaison Horizon Europe Project provides knowledge and technical solutions to limit transport infrastructures (TI) emissions, both caused by transport infrastructure itself and to which transport infrastructure contributes. This project covers the whole life cycle of TI to which extent TI design can influence and limit the overall emissions from construction, maintenance, operation and decommissioning of the infrastructure in a digital environment for next future TI.

Liaison adopts a holistic approach to tackle this challenge, because the development of particular technical solutions is not sufficient to achieve low environmental impact TI if they are not part of a broader strategy. The only effective way to ensure the implementation of paradigm-shifting technical solutions in the TI sector is to implement a governance framework (Dynamic Multi-Infrastructure Governance Framework -DMIGF) that activates, articulates, and monitors compliance with circular economy principles throughout the life of the infrastructure when developing and implementing these solutions.

Liaison develops smart and sustainable beams, rigid road pavements and improved ballast; bio-asphalt and smart pavement inspection system; intelligent tunnel control system and photovoltaic guardrails.

Keywords: Transport infrastructures · green procurement · circular economy · industrialization · digital twin

1 The European Sustainability Goals

1.1 Context

To speed up the process of circular transport infrastructure (TI) (carbon-neutral construction, maintenance, operation, and decommissioning) we need European cooperation [1] to ensure alignment and harmonization of protocols, norms and standards, while boosting knowledge generation and exchange of most advanced innovations at EU scale.

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TI is seeking for a new way of doing business. Jumping from traditional linear product development strategies to "product-as-a-service" circular concepts and business models, which must coexist with a high governance-driven sectoral structure.

It is well known that TI has a high environmental impact due to its material use, waste production and CO2 emissions (during construction and operation). In particular, "Europe must move towards a 100% renewable transportation system [2] for climate, energy and sustainability reasons in 2050 and 50% in 2030". With 136,700 km of roads [3] and 234,037 km of railways [4], Europe has one of the largest TI networks in the world.

1.2 Environmental Impacts of European TI

The European transport network has a very high environmental impact, in terms of:

- Resource consumption [5]: TI network is permanently upgraded, through the construction of new roads and railways (new corridors, elimination of high-risk sections, improvement of the capacity of critical sections, etc.), the adaptation of existing ones to comply with new regulations (security, safety, comfort, resilience, etc.), and through maintenance activities (pavement replacement, ballast maintenance, etc.) including provisions for various energy and natural resource demands. As a result, in the EU27 in 2020, 600 M tonnes of aggregates, 43.7 M tonnes of cement, 208.3 M tonnes of asphalt, including around 6.0 M tonnes of bitumen, were used.
- Energy consumption [6] and GHG emissions: the transportation sector is responsible of a third of the total final energy consumed and the CO2 generated in the EU. Additionally, the operation of some elements of the TI network, such as road tunnels, lightning systems [7], etc., requires a heavy consumption of energy.
- Economic impact [8]: From now until 2040, approximately $2 trillion in transport infrastructure investments would be needed worldwide every year to adapt TI to future needs and requirements.

It is essential that these impacts are reduced to achieve the European sustainability goals. However, TIs also have huge potential for resource generation. On one hand, most of the waste currently generated in TI interventions can be reused and recycled to create new construction materials and products. On the other hand, there is a huge unexploited potential to deploy renewable energy generation systems along with energy recovery and saving solutions.

2 Aim of the LIAISON Research Project

LIAISON is funded by the European Union's Horizon Europe program under grant agreement No 101103698. It presents four main lines of action: 1) minimizing the consumption of resources, 2) reusing available ones, 3) evolving towards a prosumer infrastructure, and 4) facilitating the market uptake by supporting procurement, legislation, and standardisation processes.

This paper focusses on the presentation of 9 of the outputs of the LIAISON research clustered in: (1) governance tools to monitor the environmental impact (2) industrialised solutions, (3) circular solutions, and (4) smart operation and maintenance solutions as described in the following sections.

3 Dynamic Multi-Infrastructure Governance Framework (DMIGF)

LIAISON is building a Dynamic Multi-Infrastructure Governance Framework (DMIGF), and Risk-Based Assessment Methodology with consideration of Life Cycle Costing based on the Level(s) methodology, providing support indicators and digital tools [9], in order to monitor the environmental impact of the design, construction, operation, maintenance and decommissioning of Transport Infra-structure. The methodology will be demonstrated with seven high impact solutions, clustered as Industrialised, circular, and smart and described in the following sections.

The DMIGF Framework is delivered as a qualitative assessment methodology for organisations to assess their current score on the path to circularity and identify goals to make the next steps toward implementation. As part of the DMIGF, a quantitative risk-based assessment methodology will be developed to evaluate the circular economy potential of TI carbon-neutral construction, Operation & Maintenance, and decommissioning strategies.

4 Industrialised Solutions for TI

This cluster of solutions includes smart and sustainable beams a rigid road pavement proving the potential of the solutions in terms of modularity, digitalisation, sustainability, and integration in smart cities.

4.1 Smart and Sustainable Rigid Road Pavement

The work is focused on the formulation of an ease-of-use geopolymer mixtures to overcome current barriers hindering industrial production and produce a new modular rigid pavement able to broaden the use of this type of pavements. This solution will put the focus also in the number and type of joint elements, the transition to the granular base through grouting, the compliance of the finished surface with the international roughness index (IRI) and surface macrotexture. This solution has two main advantages: it is based on "km0-material-use" and is whiter than asphalt so will reflect much better lighting minimising energy needs (i.e. in tunnels or during night). This "km0-material-use" strategy promoted by LIAISON is particularly interesting to take advantage of catastrophic extreme events, if can be said. Additionally, the integration of a new Weigh-in-motion (WIM) system based on optical fibre sensing technologies will enable additional savings in maintenance costs (and use of resources) up to 40% yearly [10].

4.2 Smart and Sustainable Beam

This solution is focused on the raw material saving through complex structural element design with wide application in the whole construction sector and not limited to the TI. The idea is to keep the most promising formulation identified for pavements (geopolymer based and/or recycled aggregate based compared to standard concrete) and minimize the material demand with a performance-based design and a digital manufacturing.

The innovation of this solution starts with the generative BIM-based model design to adapt the construction solution to the real demo conditions in Poland. This BIM-based model is the basis for moulds to be 3D printed using recycled thermoplastic composites. Reused steel rebars and embedded sensors will then be located in their positions using robotics before concreting. This solution can be considered a step forward from recent experiences (from 4 m beam length to 7 m). This physical solution will have an as-built digital twin for quality control and assurance providing mechanical performance data. It will demonstrate the added value of all the mentioned technologies, when rightly chained, optimising materials and fostering realistically tailored and sustainable solutions.

5 Circular Solutions for TI

This cluster of solutions is focused on resource efficiency from the perspective of material use in TI. It aims to develop and implement a selection of the most potentially impactful circular solutions for road and rail transport modes, in order to significantly lower the TI environmental impact.

5.1 Bio-Asphalt

LIAISON bridges the gaps between the laboratory and the real scale demonstrating the feasibility of the bio-asphalt technology serving in the reduction of the environmental impact of roads. To verify that bio-asphalts can be recycled at least at the same level than conventional asphalt mixtures is the key goal. To do so, both the bio-binder and bio-asphalt will be artificially aged, and the resulting materials will be tested at the laboratory. The use of bio-binders in the hot recycling of conventional reclaimed asphalt will be beneficial in terms of mechanical and environmental performance. Bio-asphalts incorporating a high rap content will be evaluated and compared to conventional recycled asphalts. Bio-asphalts have an awakened interest due to their renewable origin, huge availability and expected environmental friendliness due to replacement of a percentage of the fossil-based bitumen by a bio-binder.

5.2 Smart and Sustainable Ballast Track

This is a particular solution for a well-known railway sector problem in European East Countries (i.e. Slovenia and Croatia) that is under development. In fact, the idea is to transform existing ballast into rubber modified ballast. As lixiviation could be a weak point of this solution, a market based on geosynthetic, which will enable the development of excess confining pressure within the ballast layer, will be integrated in the full solution for track section. Besides, special noise walls made with secondary raw material (SRM) based concrete will also be designed in LIAISON supporting three missions: rail track isolation (i.e., lixiviation, floods, and fire), noise reduction and ballast confinement assurance. For controlling the ballast confinement, special pressure cells will be installed within the ballast layer to monitor the confining improvements.

5.3 Circular Materials with New Functionalities

LIAISON is advancing also in reactivating circular materials with new functionalities (i.e. energy harvesting) with added value based on thermoelectric & piezoelectric energy generators, which will be integrated within SRM-based elements. Thermoelectric generator will harvest energy from materials due to the thermal gradient inside concrete materials and piezoelectric generator will harvest energy from mechanical loading of railway track. Although this solution will be developed for load cells energy in railway the ambition is being applicable for energy harvesting in proposed WIMs for road being a real multipurpose application.

6 Smart Operation and Maintenance Solutions for TI

6.1 Intelligent Tunnel Control System

This solution will develop a Digital Twin for planning and operating energy management strategies based on open and freely usable data formats for BIM. Given that this format is very much oriented towards building design and construction, it has been necessary to propose a new semantic classification based on the pro-posed syntax, to guarantee its compatibility and interoperability. The LIAISON energy management strategy is focused on tunnel ventilation control systems going from switch on-switch off operation to variable frequency drives (VFDs) to control fan speed and reduce electricity consumption. The innovation in terms of lighting is focused on the development of automatic algorithms to optimize the economic performance of the system.

6.2 Photovoltaic Guardrail

The Photovoltaic Guardrail facilitates the transformation of a passive TI element into an active one. This innovative solution integrates already existing PV flexible generation systems with current and standardised guardrails for roads. This innovation offers a product family concept by creating interchangeable elements, suitable for replacement in case of same beam, same post or same cover leading to the optimization of the manufacturing and stock. Reduction of the energy need of TIs and of CO2 emissions is expected as result of the self-production and reuse on site of renewable resources.

6.3 Pavement Management System

Regarding the damage detection for pavement maintenance LIAISON is developing a pavement distress detection system using Deep Learning architectures. This includes a video-based and vehicle-mounted system to be used for image collection. For a more precise, and higher-quality, a low-cost, and fast-acquisition camera will be mounted on the exterior of the vehicle. The concept for promoting this solution is to move forward from dedicated intensive visual inspection campaigns to less demanding and safety procedures. In conclusion, inspection time by operators and inspectors will be reduced, improving safety conditions.

7 Conclusions

This paper has provided an overview of the planned activities of the LIAISON project. As mentioned previously, the circularity implications of the above-described smart solutions for TI will be quantified through the DMIGF, based on various KPIs which consider not only circularity, but also the uncertainty and risk in delivering innovative methods. Given that the project started in mid-2023 (36 months long), it is too early to draw conclusions on the challenges posed by the project. However, as the project is based on the existence of prototyped solutions, it is expected to move rapidly towards validation of case studies in real and operational environments.

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Enhancing Rail Vehicle Structural Performance Through High-Recyclability Thermoplastic Composite Lightweight Components

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Abstract. In numerous industries beyond rail vehicle technology, the utilization of continuous fiber reinforced plastics (FRP) has already gained prominence alongside conventional metallic materials due to their exceptional lightweight potential. However, the application of such materials in rail vehicles encounters limitations, including stringent fire protection requirements, the need to establish new repair processes, feasibility of recycling, and higher manufacturing costs. To address these challenges and facilitate the structural implementation of FRP in rail vehicles, a comprehensive approach has been developed. This approach primarily encompasses material selection, design, simulation, and relevant manufacturing technologies, while also considering the intricate interactions among these factors. Through the successful application of this approach, a remarkable breakthrough has been realized: the design and fabrication of an exceptionally robust, high-impact structure positioned beneath the car body of a high-speed train. One cornerstone of this approach is a multi-stage material selection process that meticulously evaluates both general and rail-specific requirements. These encompass fire safety, thermal stability within operational temperature ranges, recyclability, static strength, fatigue resistance, manufacturability, and numerous other critical factors. Leveraging the outcomes of this rigorous material selection process, an innovative design strategy guided by advanced simulation techniques was employed to craft a resilient and cost-effective component using carbon fiber-reinforced thermoplastics (CFRTP).

Keywords: Lightweight design · Circularity · Recyclability · Rolling Stock · Composite · Energy Efficiency

1 Screening of Fiber Reinforced Thermoplastics for Rolling Stock Applications

Fiber-reinforced plastic composites offer numerous advantages over conventional materials, such as metals. Carbon fiber-reinforced plastics (CFRP), in particular, hold the potential to realize high-strength and exceptionally rigid structures while maintaining minimal component mass. Nonetheless, a significant drawback of FRP materials often arises from slow manual manufacturing processes, leading to elevated costs, extended

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cycle times, and challenges in quality assurance [1]. Furthermore, recycling FRP materials with thermoset matrices after their lifecycle remains a major hurdle, given the intricacies and cost-intensive nature of industrial fiber-matrix separation and subsequent recycling for this material category [2]. The use of FRP materials with thermoplastic matrices has been gaining strong momentum in the automotive and aerospace industries for several years [3]. Unlike thermosets, thermoplastics can undergo repeated melting, which is particularly attractive regarding recycling. The melt can be processed using various established manufacturing techniques, necessitating a high degree of automation due to the elevated process temperatures and pressures. Consequently, process times can frequently be reduced from hours to minutes compared to thermosets. At the end of a component's lifecycle, the material can be re-melted and reprocessed. Some thermoplastics also exhibit exceptional fire-resistant properties, capable of meeting stringent EN 45545 requirements without the need for additional protective coatings [4].

Before introducing new materials into rolling stock components however, they must first be qualified. The technical and normative requirements to be met by a particular component or its material depend to a large extent on the intended use and location of the component on the vehicle. In this paper, the development process of a CFRTP cladding component intended for use on the exterior of rail vehicle floors will be investigated. The usability of new materials for this application is not only determined by rail-specific criteria like fire, smoke, and toxicity (FST) performance, temperature resistance, and resistance to environmental factors but also special properties such as resistance to flying ballast. To identify the most suitable thermoplastic fiber-reinforced composite material for structural components in rail vehicles, a multi-stage testing protocol has been developed. These tests comprehensively evaluate the mechanical properties of the materials in conjunction with other considerations, including processability, cost, availability, and material quality.

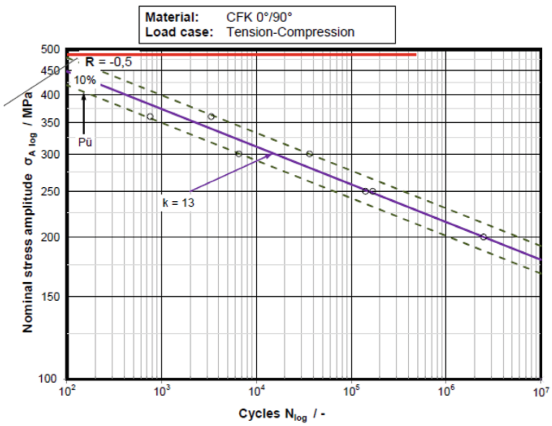

Fig. 1. Example of the S-N curve for a biaxial CFRTP composite at a stress ratio of R = −0.5

In the final stage of the developed testing protocol, fatigue tests were conducted under different load conditions, encompassing up to 10 million load cycles for varying stress ratios and laminate layups. The knowledge of the resulting material properties enables the determination of fatigue strengths and its sensitivity to stress ratios for viable laminate structures. Therefore, it allows the numerical calculation of components considering cyclic loads. Figure 1 provides an illustrative example of the S-N curve for a biaxial CFRTP composite at a stress ratio of R = −0.5

2 Simulation Driven Component Design

A simulation-driven development approach was selected to engineer the component. In the initial phase, a comprehensive design space analysis was undertaken (see Fig. 2 left). The component was partitioned into two distinct sections: an external shell structure (depicted in yellow) and an internal rib structure (displayed in blue and green). The external shell exhibits a low complexity, consistent surface characterized by unidimensional curvature, and a uniform thickness throughout. These attributes allow for the integration of continuous fiber reinforcements during the manufacturing process. This is achievable because the molten thermoplastic need not fill any cavities on this side of the component. The uninterrupted fibers maximize the in-plane strength of the component and provide resistance against ballast impact, ensuring that no penetration occurs during operation. The inward facing part of the component is more complex in shape. In order to obtain the desired structural rigidity, the application of a rib structure is necessary. Given the complex geometry of the required rib structures, it is not feasible to mold them using continuous fibers. Therefore, the inner section of the component will be constructed using long fiber thermoplastics (LFT). These shorter fibers, ranging from approximately 10 to 25 mm, allow for material flow during the molding process. Although certain rib positions are predetermined due to the need for connection points for seals, locks, and other components, a substantial portion of the available design space can be optimized to maximize the torsional and bending stiffness of the component.

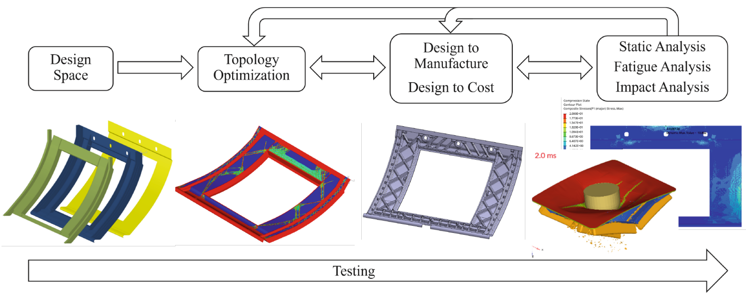

Fig. 2. Simulation driven design approach. Left: design space analysis with outer shell (yellow), predetermined ribs (blue) and available design space (green); middle left: result of the topology optimization; middle right: process friendly redesign; right: simulation results. Image courtesy of CG Rail GmbH, reproduced with permission.

To optimize the utilization of materials, topology optimization is employed to determine the optimal positioning of additional ribs. The optimization algorithm is configured to target the highest possible stiffness of the component under specific load conditions. Additionally, various boundary conditions are imposed on the model, including maximum static stress limits, total part mass constraints, draft angle, draft direction, maximum rib thickness, and other factors. The outcome of the optimization process, as depicted in Fig. 2 in the middle left, is an unrefined design, which must subsequently be adjusted to meet manufacturing prerequisites (Fig. 2 middle right). The final rib dimensions, including appropriate height-to-width ratios and draft angles, have been experimentally verified and integrated into the design. In the final phase, the manufacturable model undergoes a series of finite element analyses to assess whether it meets the predefined requirements for static strength, fatigue resistance, and impact durability. A selection of these simulation results is showcased in Fig. 2 on the right, while the setup and results of the impact analysis are also detailed in Fig. 3. These results illustrate the susceptibility of the low-strength, high-stiffness LFT rib material to fracture upon impact, contrasting with the capability of the high-strength, high-stiffness continuous layup of the outer shell to withstand impact. This outcome underscores the distinct functions of the previously segregated areas within the component. The outer shell primarily provides structural strength, while the inner rib structure primarily enhances the component's stiffness. Accompanying material and manufacturing tests were conducted to validate the assumptions embedded in the models.

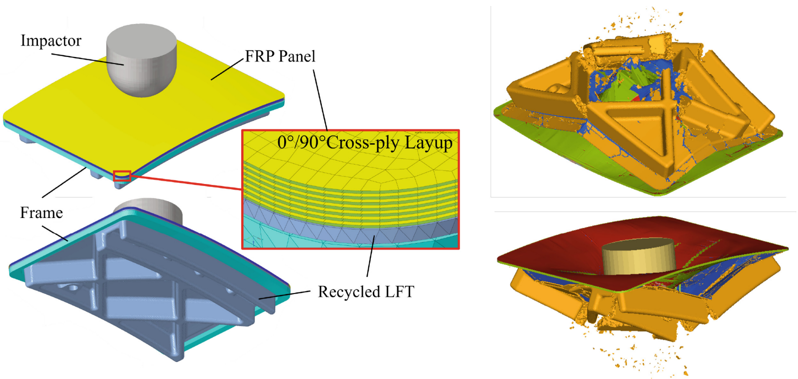

Fig. 3. Left: finite element model of the impact analysis containing impactor, target, and suspension; right: single timestep result of the impact analysis. The impactor inflicts heavy damage but does not penetrate the component in a worst-case 90° impact scenario. Image courtesy of CG Rail GmbH, reproduced with permission.

3 Compression Molding

In addition to the design of the component made from fiber-reinforced thermoplastics, the production and associated process technology is a major challenge on the way to the wider use of this group of materials in rail vehicle technology. Thermoplastic manufacturing processes such as injection molding or compression molding are very productive and can be automated to the greatest possible extent and thus stand out from most processes with a thermoset matrix. However, the equipment used to manufacture components from fiber-reinforced thermoplastics is more cost-intensive due to the high processing temperatures and process pressures required, so that a larger number of units is necessary to justify the tooling and machine utilization from an economic point of view. The higher investment costs are quickly offset, in particular by the large material output of the processes, since the process times can be reduced from several hours to a few minutes [5]. In the example considered (planned production of 2000 components per year), a compression molding process with a two-part die was selected (see Fig. 4). In contrast to manufacturing components via injection molding, the cost of mold construction is significantly lower when employing the described compression process, rendering it economically viable for smaller production series.

During the manufacturing process, pre-cut CFRTP plates, composed of either continuous fiber laminates or LFT material, are placed on a tray and subjected to convection oven heating. Once heated, the molten materials are lifted by pneumatic needle grippers and deposited within the mold. The hydraulic press, upon closure, forces the materials to assume the precise shape of the mold's cavities. While the continuous fiber laminate barely undergoes any deformation, the LFT material flows into the cavities, forming the ribs. As the tooling is maintained at a temperature below the solidification point of the thermoplastic materials, the melt rapidly cools and can be demolded in approximately 3 min. Subsequently, the multi-tray oven efficiently preheats the next batch of material, ready for immediate placement in the mold. Following demolding, the composite part is allowed to return to ambient temperature and is subsequently prepared for subsequent coating and assembly procedures.

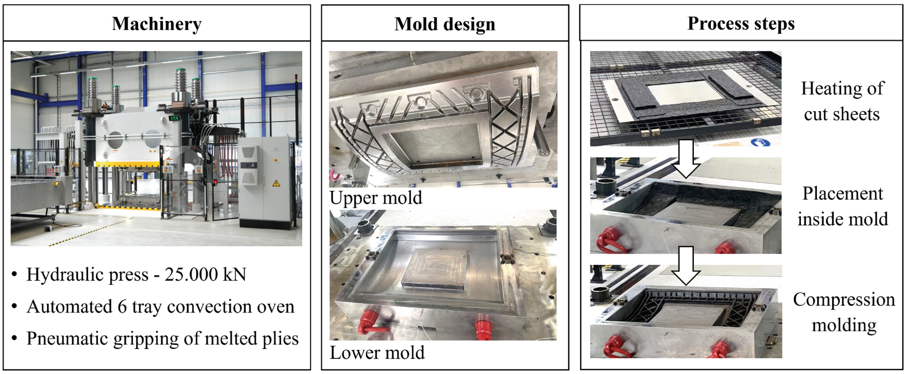

Fig. 4. Manufacturing setup. Left: hydraulic press; middle: upper and lower halves of the two-piece mold; right: basic processing steps of the compression molding process. Image courtesy of CG Rail GmbH, reproduced with permission.

Notably, the thermoplastic CFRP component developed consists of 76% recycled material (LFT ribs) and only 24% virgin material (continuous shell). The fiber-reinforced thermoplastic portion of the entire structure is made of the same material, which means that waste from the component trim and the component itself can be recycled again at the end of its life cycle.

4 Conclusion

In the pursuit of facilitating the integration of fiber-reinforced thermoplastics into rolling stock applications, a comprehensive framework for material screening and selection was developed. Through rigorous testing and evaluation, a singular material emerged as the optimal choice, subsequently undergoing detailed characterization to determine the required material properties for the design of a fatigue and impact-resistant component for rail vehicles (Fig. 5). This component was designed in strict compliance with relevant industry standards, load considerations, and various influencing factors, while considering the subsequent production process. A simulation-driven design approach was used to maximize the inherent advantages of the new materials and the associated manufacturing processes. Subsequently, process parameters were determined in an industrialized press process and numerous components were manufactured. In comparison to traditional aluminum construction, this lightweight component showcases mass savings, approximating 30%. Furthermore, it can be manufactured through a fully automated, near-net-shape process, at a cycle time of only 3 min. This novel component also offers a wide range of other advantages such as the integration of functional elements, improved corrosion behavior and better mechanical properties.

Fig. 5. Fully assembled lightweight component [6]

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Supporting the Planning of Dedicated CargoTube Links Through Simulation

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Abstract. CargoTube adopts the hyperloop concept and has the potential to ultimately reducing the total energy requirement of transportation and therefore minimizing the Greenhouse Gas (GHG) emissions beyond the capabilities of surface or airborne transport. However, CargoTube relies on more conventional and readily available track technology, like a train or streetcar, to guide and propel the vehicle within the tube. Large diameter steel tubes such as those used in gas or water pipeline infrastructure can be adopted. The CargoTube concept results in a balance between performance, efficiency, and lifetime cost to provide an intermodal cargo transport system for industrial logistics and transportation corridors.

This paper presents how the planning of specific CargoTube routes can be supported by means of an example drawn from the EU-funded research project ePIcenter (epicenterproject.eu/). The example connects a Logistics Service Park (LSP) with an automobile production site. The application of the planning is supported by a discrete event simulation to assess the impact of innovative transportation technologies by simulating selected Key Performance Indicators (KPIs) under different technological assumptions.

Keywords: Hyperloop · CargoTube · Sustainable Transport · Simulation · Discrete Event Simulation

1 Introduction

Hyperloop is a transportation system that is used to transport goods fast and in high volumes for short and middle-distance logistics complementing the railway network. A hyperloop system comprise three main elements: tubes, pods, and terminals [1]. The tube is a sealed, low-pressure system. The pod is a coach which might be normally pressurized and that runs considerably free of air resistance inside this tube. Magnetic

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levitation and guidance minimize mechanical friction, propulsion is powered electrically. The terminals handle pod arrivals and departures [2].

CargoTube adopts the hyperloop concept and has the potential to ultimately re-ducing the total energy requirement of transportation and therefore minimizing the Greenhouse Gas (GHG) emissions beyond the capabilities of surface or airborne transport [3]. However, CargoTube relies on more conventional and readily available track technology, like trains or streetcars, to guide and propel the vehicle within the tube. The use of existing and well-established technology and "stock" components allows CargoTube to significantly reduce the costs associated with development, in addition to facilitating rapidly upscaling transportation networks. The CargoTube concept results in a balance between performance, efficiency, and lifetime cost to provide an intermodal cargo transport system for industrial logistics and transportation corridors [3].

For the planning of the layout and the implementation of such a system many questions need to be answered ranging from the actual routing, layout of terminals, capacity (number of tubes, pods, etc. in relation to planned throughput) to infrastructure setup and operational costs.

The remainder of this paper presents an example that connects a Logistics Service Park (LSP) with an automobile production site. A discrete event simulation model has been built to allow the evaluation of different possible setups and their logistics performance.

2 Method

The discrete event simulation model that has been built using the JaamSim simulation system [4]. The central elements of the model are two tubes going from a Logistics Service Park (LSP) to a manufacturing plant and vice versa. The layout of the simulation model is shown in Fig. 1.

First, a basic data spreadsheet has been defined to collect the necessary input data and to calculate some basic parameters. The spreadsheet is divided into the following sections:

- Objectives: Calculation of the amount of cargo transported each day.
- Constraints: This section mainly collects the size of the boxes and calculates the diameter, total volume, and transport volume per box. The diameter of the box is needed to select the right diameter of the tube.
- Hyperloop Layout: In this section the amount of steel and concrete needed for the tube(s), rails, and pillars are calculated depending on the length, diameter, etc. of the planned system.
- Pumps: This section calculates times and costs for generating and maintaining the vacuum in the tubes based on the specific properties of selected pumps.
- Pod Layout: The pod layout includes the minimal pod diameter, its length, and the blockage ratio.
- Cargo Bay Layout: The cargo bay layout includes the minimal length and the re-evacuation time necessary after any loading or unloading activities under normal pressure.

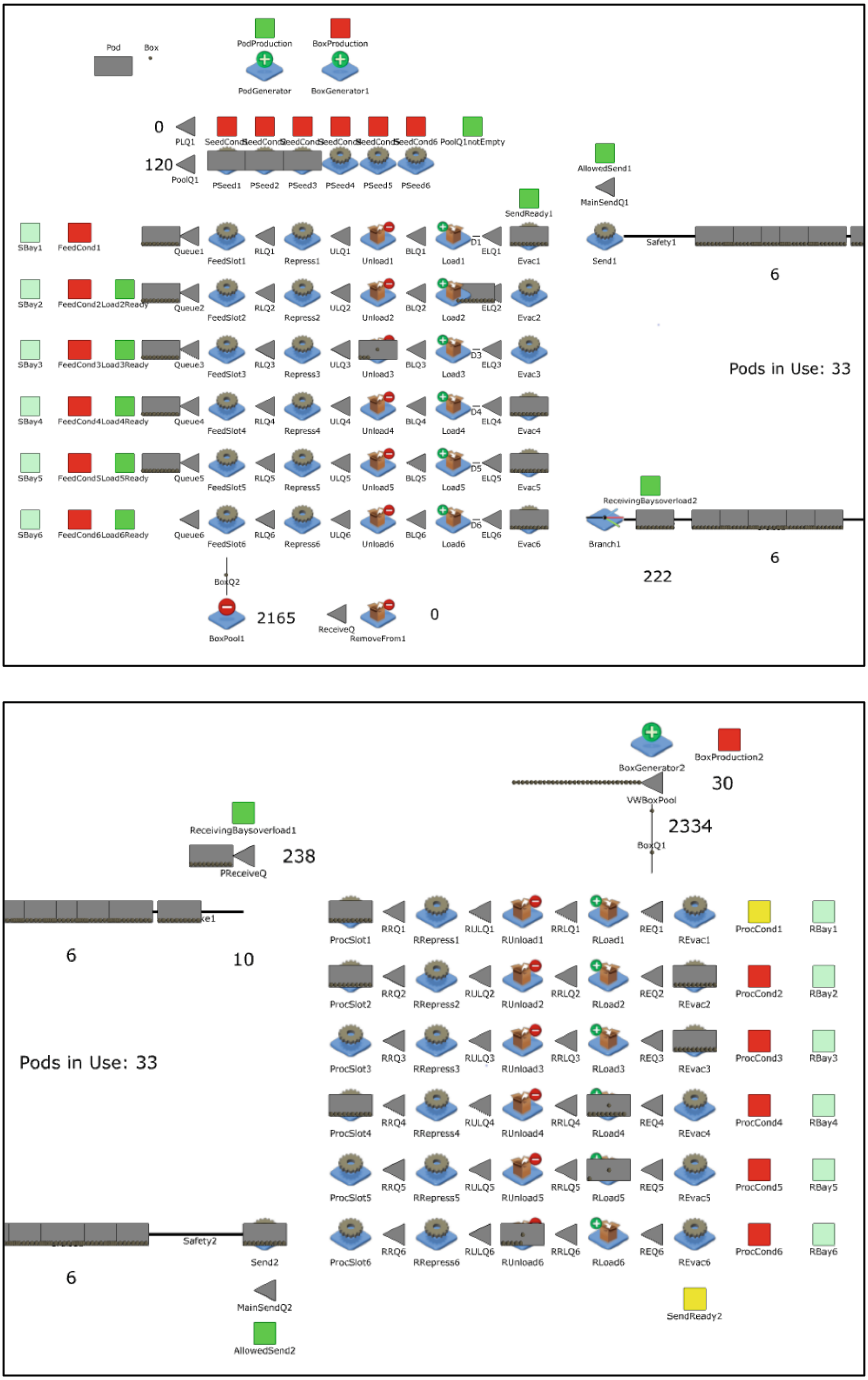

Fig. 1. JaamSim CargoTube simulation model while running. Top is the left side (LSP), bottom is the right side (manufacturing plant).

- Handling: This section collects estimated repressuring and loading/unloading times and calculates the total handling time per pod in a cargo bay.
- Operation: This section calculates some basic operational parameters like travel time, maximum number of pods per day, the minimum number of bays, and the maximum number of pods in the system.

3 Results

The basic data spreadsheet already allows an assessment of the capabilities and performance of the planned CargoTube system, but it is always difficult to assess these numbers in a dynamic environment. Questions concerning the bottlenecks of such a system can only be answered by a discrete event simulation model [5] which takes the basic data as input.

Figure 1 shows the layout for the discrete event simulation model. The central elements are the tubes going from the LSP to manufacturing plant and vice versa. On each side is a terminal with six bays which can be individually switched on and off (e.g. for simulating maintenance). In each of the bays the single pods are running through a process of waiting (when the bay is in use), repressuring, unloading and/or loading, and evacuation. When the process in a bay is finished the pod is sent into the tube when a specific safety distance from the last pod has been reached. The handling process on the other side is the same with the exception that empty boxes are loaded to be sent back. The model is parameterized in various ways which allows the evaluation of relevant transport logistics indicators like timeliness and throughput under different utilization scenarios.

Analyzing the basic data and the constraints listed above, initial experiments with the simulation model provide the following insights:

- Around 12,600 boxes must be transported each day.
- The CargoTube system is expected to have two tubes with a length of 12 km, one tube for each direction.
- The inner diameter of the tube is defined to be 2.0 m resulting in around 19,140 t of steel (for tubes). The tubes do not have a concrete floor inside the tube. Further steel and concrete are needed for the rail system and the pillars.
- The total volume within the two tubes is around 75,000 m^3.
- With two pumps the time for tube evacuation down to 10 mbar is around 5 days.
- If a pod used in the tube carries 10 boxes it should have the length of 12.6 m.
- Assuming a repressure time and automated unloading/loading time of one minute each result in a handling time of 11.41 min including the evacuation.
- The total travel time for a pod is 5,5 min including acceleration and braking.
- The whole system can transport more than 16.000 boxes from the LSP to the plant using six bays on each side and running fully loaded (no waiting times).
- The maximum number of pods in the system is 33 (compared to the calculated number of 36).
- With only five bays in operation on each side, the system is still capable of transporting more than 13,500 boxes per day.

- With only four bays in operation on each side, the system can transport more than 10,500 boxes per day.
- With specific demand curves which simulate the uneven demand of supply during the hours of a day there are a few waiting times which do not last longer than 60 min.

4 Conclusions

The design and modelling of a CargoTube system aims to understand how such new concepts in transportation have an impact on freight transport and their contribution to a major reduction of greenhouse gas emissions. Noise, weather exposure, safety, total energy consumption, and the direct GHG emissions inevitably linked with freight transportation will be substantially reduced. Emerging solutions need to be carefully planned, analyzed, and evaluated, to understand what their contribution to a sustainable transport system can be.

The example demonstrates that such a CargoTube can supplement the conventional transport modes. Noise, particulate matter, pollution emissions, and light exposure to the environment, residents, and wildlife are effectively cut off by the low-pressure tube ecosystem. Reduced energy storage requirements and further decreases in environmental impacts result from the use of electric propulsion and continuous recharging in the operation of the enclosed system. The CargoTube design is reliable and flexible while automation reduces costs and personnel requirements. In addition, a high level of automation in a closed tube supports a resilient transport system which can withstand extreme weather conditions. The confined low-pressure environment provides a high level of security for the goods transported. This kind of dedicated, fully automated transport mode supports industry optimization workflows for a reliable just in time supply chain. Significant reduction in road traffic and congestion, especially in urban and densely populates areas, can be achieved.

The only disadvantage is the evacuation time of around three days for the given example, which may take place when maintenance inside the tube is required. For such circumstances it needs to be proved that the pod traffic can start earlier with reduced speed while the tubes are still evacuated.

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A Novel Light Train Using Modular Electrical Power Traction

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Abstract. This article introduces a simulation tool which allows to validate the dimensioning of the energy sources and the energy management system of a hybrid train, this solution is proposed as part of an innovative France project called TLI (Innovative Light Train). For this purpose, the aim of this article is to propose a modeling of these powertrains by using the energetic macroscopic representation (EMR). Finally, energetic simulation results are shown, using real data of two train missions in France.

Keywords: battery · energetic macroscopic representation (EMR) · fuel cell · light train · modelling

1 Introduction

In France, the secondary rail networks (UIC 7 to 9 SV: defined by the International Union of Railways) represent a significant part of the national railway network, accounting for approximately 42%, with a length of 12047 km from a total of 28932 km. Only 15% of these lines are electrified, mostly single track with a low-capacity operating system.

A new project called TLI proposes an innovative solution to replace the diesel rolling stocks by hybrid electrical trains, using energy sources as batteries and hydrogen. Therefore, this solution gives relevant solution for decarbonization.

The main contribution of this project is to propose a rolling stock system which can be powered by modular energy sources with lighter mass compared to the existing diesel train X72500 and X73500. A static or dynamic charge of the train batteries can be done through a pantograph on the 15% electrified parts of the network either it's a 1500 DC or 25 kV AC lines. To obtain a higher autonomy specially in non-electrified lines, another version of TLI used hydrogen and batteries is also proposed.

For a precise assessment, this paper proposes a modeling of the power chain to define and validate the necessary sizing of the batteries and giving the possibility for this innovative solution to be studied before their real implementations. Energetic Macroscopic Representation (EMR) is used to improve the organization of models as well as the development of the control structure. This approach is used in several field such as: railway [1], electrical and hybrid vehicles [2], micro grid [3]. A judicious manner is

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needed to manage the energy flows respecting to the physical constraints of each source. Thus, energy management system (EMS) is proposed to split the power between the embedded energy sources and catenary. Several methods of EMS can be implemented in the future: optimized based methods [4], rule-based methods [5] or machine learning based methods [6].

2 Light Train Modeling

2.1 Light Train Architecture

The innovative light train (TLI) project is characterized by its light weight objective of 48t, and a maximum speed limited to 120km/h, it can be powered by either a 1500 V DC overhead line or a 25 kV AC line. In addition, it is equipped with the lithium batteries that power the train during the non-electrified zones for an autonomy of 200 km. The batteries can be recharged when the train is stationary and during its traction via the catenary or by energy recovered during braking. This operation is possible by a bidirectional DC/DC converter connected between the battery and the 800 V DC BUS. These topologies allow to obtain two versions of TLI called: dual-mode Battery Electrical Multiple Units (BEMU) 1500 V DC and 25kV AC.

For higher autonomy on non-electrified rail lines, a hybrid solution has been proposed, it is named mono-mode hybrid hydrogen (H2) version. This consists of coupling the batteries with a fuel cell (FC). A Hybrid hydrogen traction would give greater autonomy than the battery version, without emitting any local carbon emissions or pollutants. This version allows to achieve an autonomy in range of 1000km but does not allow to use catenary for traction or recharge it traction battery.

This paper focuses on the modeling of dual-mode BEMU 1500V DC and H2 version presented in Fig. 1. In the BEMU 1500V version, the catenary represents the energy source, whereas in the H2 version this energy source is replaced by the FC system.

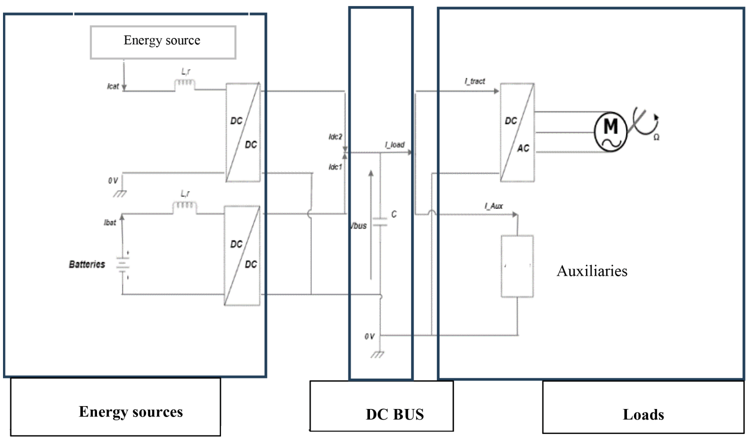


Fig. 1. TLI dual-mode BEMU 1500VDC and mono-mode hybrid H2 versions architecture.

According to Fig. 1, TLI model can be decomposed into three main parts:

- Energy sources: it contains the batteries and catenary or fuel cell system, with the smoothing inductor to reduce the current ripple and DC/DC converter.
- DC BUS: it is represented with capacitor.
- Load: it includes the auxiliaries, which are considered as constant loads, and the traction part which include the motor, as well as the mechanical parts: chassis, wheel, gearbox, and environment (resistive forces).

2.2 Modeling

Energetic Macroscopic Representation (EMR). EMR is a graphical description tool based on the physical interactions (action/reaction principles) and causality between each component which can highlight the power exchanged in the system [7]. It is important to emphasize that EMR is not a modeling method, but a method to organize multi-domain system modelling [8]. It organizes the system into interconnected basic elements (see Fig. 2): source of energy (green oval), accumulation of energy (orange crossed rectangle), monophysical (orange square) or multiphysical conversion (orange circle), and distribution of energy (double orange square).

TLI Modelling. As explained in previous sections, both TLI versions have the same architecture, except for the hydrogen version where the pantograph system is replaced by the hydrogen fuel cell system. The final models of the dual-mode BEMU 1500 V version and mono-mode hybrid H2 version are presented in Fig. 2.

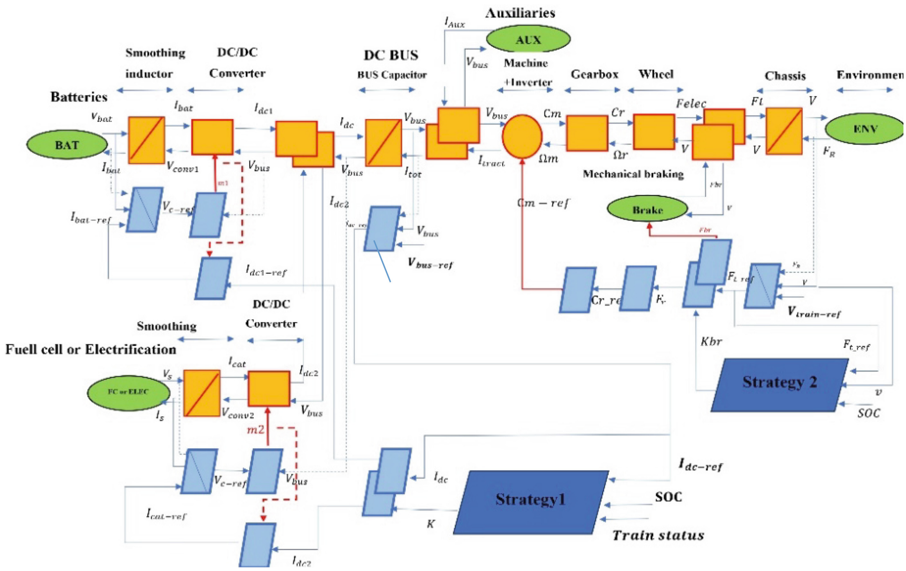


Fig. 2. EMR and inversion-based control of BEMU 1500VDC and hydrogen versions.

- The energy sources considered as voltage sources are presented by the green oval shapes they are modeled by the following equations:

$$V_{\text{bat}} = \mathrm{E}_0(\mathrm{SOC}) - \mathrm{RI}_{\text{bat}} \tag{1}$$

where V_{bat} is the battery voltage, SOC is the battery state of charge, I_{bat} the battery current, R is the internal resistance of the battery.

FC is modeled as a voltage source defined using a second-order polarization curve, for more details about the fuel cell model see [3].

The environment is considered as source of resistive forces expressed as below:

$$F_r = F_{RA} + F_{gra} = A + BV + CV^2 + m_s * g * i \tag{2}$$

where A, B, C are the coefficient of the resistive forces, g is gravity, m_s is the static mass, i is the slope.

The catenary is modeled with a perfect voltage source of 1500V, and the auxiliaries consume a constant power P_{aux}.

- The accumulation elements (orange crossed rectangles) such as the inductor and capacitor impose the energy variables, which are the source current i_s and i_{bat}, the DC bus voltage V_{bus}, train speedV_{train}:

$$\mathrm{V}_{source} - \mathrm{V}_{\text{convi}} = L_i \frac{\mathrm{di}_{source}}{\mathrm{dt}} + \mathrm{i}_{source} R_i \tag{3}$$

where the V_{source} is the source voltage, $\mathrm{V}_{\text{convi}}$ is the DC/DC converter voltage,L_i is the inductance of the smoothing inductor and R_i is its internal resistance.

$$I_{tot} - I_{trac} = C_{bus} \frac{dV_{bus}}{dt} \tag{4}$$

where I_{dc} is a s ource current, I_{trac} is the load current, C_{bus} is DC bus capacitor, V_{bus} is the DC bus voltage

$$F_{tot} - F_r = m_d a = m_d \frac{dV_{train}}{dt} \tag{5}$$

where F_{tot} is the total forces, F_r is the resistive forces, m_d is the dynamical mass, V_{train} is the train speed.

The DC/DC converters are presented by mono physical conversion (orange squares) which convert current and voltage according to the modulation ratio m_i.

$$V_{conv} = V_{bus} * m_i \tag{6}$$

$$I_{conv} = \mathrm{i}_i * m_i \tag{7}$$

where V_{conv} is the converter input voltage and I_{conv} is the converter output current.

The inverter and machine are considered as multiphysical conversion that converts the electrical variables to mechanical variables.

$$I_{tract} = \frac{F_{tot-ref} * V_{train}}{\eta^k * V_{bus}} \tag{8}$$

where I_{tract} is the traction current, $F_{tot-ref}$ is the total force reference, η^k is the motor efficiency, k is the breaking coefficient (k = −1 i.e. electrical traction, k = 1 i.e. electrical breaking).

Control and Energy Management. The control structure is deduced systematically by direct or indirect inversion of the EMR (Inversion-based control) [7], in our case, the variables to be controlled are BUS voltage V_{bus}, train speed V_{train} and the current sources. The main function of the control is to maintain the train speed close to the specified reference speed and to regulate the DC bus voltage. In this paper, a proportional integral control is used in the two cases. The parameters of the PI controller are calculated using the pole placement method. The strategy 1 (blue bloc in Fig. 2) represents the rule-based energy management strategy that split the power demand between the different sources, depending on the batteries SOC and the electrification. The strategy 2 in Fig. 2 generates the mechanical braking forces needed to stop the train, these forces are calculated according to the batteries SOC and the train speed.

3 Simulation Results

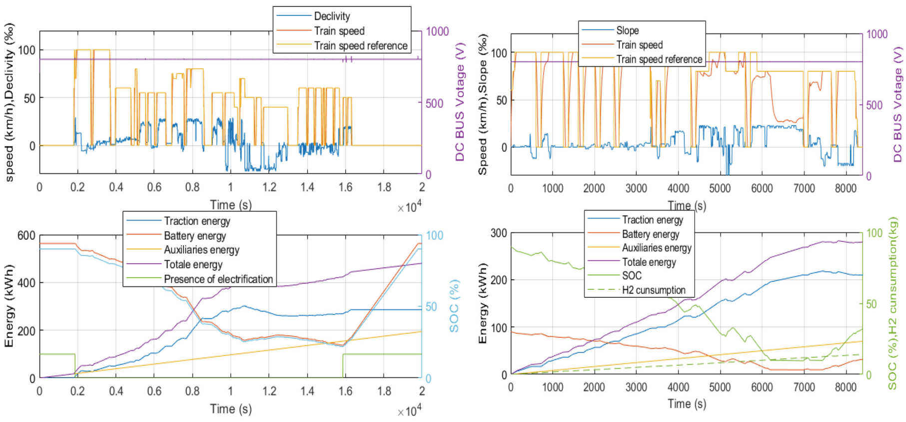
To validate the sizing of energy sources, different simulations are considered. Each version is tested on day missions presented in Table 1.

Table 1. General line characteristics for the version BEMU 1500V and hydrogen

Use cases	Version	Distance	Electrification
Mission A	BEMU 1500V	198.2 km	6.15 km
Mission B	Hydrogen	156.5 km	None

Figure 3 Simulation results of BEMU 1500 V(a) and hydrogen(b) versions. The figures illustrate the energetic results of real missions corresponding to the hydrogen and dual-mode BEMU 1500VDC versions. From these graphs, we can observe that the speed of the train and the bus voltage respect the references signals. In both simulations, DC bus voltage is properly regulated around the reference (800V), some voltage peaks (2% at maximum) are observed due to the energy recovery and energy absorption during the braking and traction operations.

For the dual-mode BEMU 1500VDC (see Fig. 3 (a)), the batteries are recharge in electrified areas (via the pantograph by static or dynamic recharging) as well as in slope declivity zones. During the whole mission, the batteries SOC is greater than 10%, which validates the sizing of the battery in this version. In the hydrogen version (see Fig. 3 (b)),



(a) (b)

Fig. 3. Simulation results of BEMU 1500 V(a) and hydrogen(b) versions.

the FC works with its maximum power in the traction phases and recharge the batteries in the static and dynamic phases of the train. In this case, in the time range from 6100s to 7000s, the battery SOC reaches 10%, and the train speed does not reach the reference speed. This means that the train will be delayed, and the sources sizing is not sufficient for this mission. The solution is either to resize the energy sources, or to adjust the train timetable.

4 Conclusions

In this paper, energetic modeling of dual-mode BEMU 1500VDC and hybrid hydrogen light trains is presented by using EMR. This method allows the various elements of the drive train to be represented according to the action/reaction and causality principles. This representation method facilitates the control structure by using the direct and indirect inversion.

The simulation results also show the performance of the energy management system and prove that the sizing of the energy sources is adequate and capable of covering the energy and power requirements respect to the various constraints of the secondary rail networks (UIC 7 to 9). Although validation on a test bench is still necessary to reproduce real power flows and validate the performance of the energy management system in real time. In addition, this experimental stage will also enable us to study other physical phenomena that were not considered in the assumptions used in the simulation model, in particular battery dynamics and the interaction between the catenary and the train.

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Alternative-Driven Public Vehicles Ranking Based on Consumption and Operating Cost Considering Number of Passengers Transported

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Abstract. The current commercial electric and non-fossil-fueled vehicles can be an alternative to the polluting diesel vehicles used nowadays. However, in the current development phase, the main problem is their short range and/or expensive purchase cost. Accordingly, our main goal was to compare and rank selected vehicles operated in cities based on the established compliance indicator. The novelty of the paper is that it compares vehicles using multi-criteria analysis based on different criteria, including energy cost. The vehicle- and route/operational parameters were described for public transport bus-, taxi- and electric scooter services. The mobility services were evaluated and ranked based on the groups of vehicle- and contamination criteria. The method is applied as a case study using fuel consumption and contamination databases for Germany, Hungary, Poland, and Sweden. This method can be used by municipal transport operators to plan which service should be implemented on a given route according to current and future circumstances and needs.

Keywords: Road Traffic · Alternative-driven Public Vehicles · Operating Cost · Urban Public Transport · Ranking · Evaluation

1 Introduction

Two main challenges related to traffic organization in large cities are observed: reducing harmful emissions and congestion. These challenges impact the decisions made by city transport operators. Alternative-driven vehicles (gas-powered, electric, etc.), buses, as

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well as taxis that use the bus lanes, and micro-mobility devices (e.g., scooters) are introduced in city road transport to ensure fast, efficient, and environmentally friendly (lower noise/air pollution) traffic. However, decision-makers often do not possess the information needed to make the right decisions. In some cases, expensive and ad hoc developments could be implemented, which do not provide optimal solutions.

Accordingly, the research question was defined as follows: 'Which vehicle type provides the most appropriate service in dense urban traffic on a road section prone to congestion?'. The TOPSIS, a multi-criteria decision-making method, was adapted to rank the alternative-driven (CNG, electric) and diesel-fueled public vehicles. The study is part of a scientific research project that aims to support public transport operators in the efficient decarbonization of transport modes while optimizing budgets, emissions, and energy consumption.

2 Literature Review

Different parameters influence urban road traffic. In the available studies, the vehicle and route parameters are rarely analyzed together. Mostly, analytically derived vehicle parameters were considered to characterize trips and journeys. The consumption of vehicles (either diesel [1] or electric [2, 3]) was analyzed and compared [4]. Moreover, four basic operating parameters influencing energy consumption have been examined: stop distance [5–7]; topography [6–10]; and passenger load [5–7, 9]. Furthermore, environmental and resource considerations about electric bus fleet operation are mentioned [11].

The simplest way to reduce local emissions is to change the fleet to alternative powered vehicles. One of the major problems observed is that public perception considers electric motors the cleanest propulsion systems. These drivetrain usages in urban environments emit less pollution (noise and air), although few research studies show energy production and vehicle disposal calculations [12]. It is important to note that the cleanest technology for cities would be the electricity supplied dynamically to vehicles from the catenary system, avoiding polluting and costly energy storage [13]. However, it should be highlighted that the energy consumed by vehicles should be considered not only during their use but also during production and disposal.

The Multi-Criteria Decision-Making method can be applied to analyze alternative-powered vehicles [14]. A sophisticated version of this selection method is the matrix-based weighting method, the TOPSIS method. This method has been used previously for the selection of vehicles [15], electric buses [16], and rapid transit systems. Therefore, it was used to conduct further investigations.

3 Material and Methods

The TOPSIS method was applied to determine the compliance indicator. This indicator expresses the suitability of the transport services for the city. For simplicity, energy consumption calculations were based on average and continuous acceleration and deceleration, expressed with the average energy consumption of the vehicle.

The considered parameters within the developed method are divided into two groups: (i) v_α vehicle parameters (19 parameters), (ii) r_β route and operational parameters (6 parameters), shown in Table 1. The maximum speed and the range were neglected as these data may be derived from the basic parameters. Applying calculations, the transport service dependence on traffic and congestion were considered.

Table 1. Vehicle and route parameters.

v_α vehicle parameters	r_β route/operational parameters
v_1: Maneuverability [-]	r_1: Trip length [km]
v_2: Shortest acceleration time [s]	r_2: Average usage time per trip [h]
v_3: Vehicle length [m]	r_3: Number of dedicated lanes [-]
v_4: Consumption rate [kWh/km] [liter/km]	r_4: Passenger load in average trip [pax/trip]
v_5: Battery/Tank capacity [kWh] [liter]	r_5: Energy price [$/kWh] [$/l]
v_6: Vehicle average mass [kg]	r_6: Dedicated driving speed [km/h]
v_7: Maximum starting power [kW]	
v_8: CO_2 emission rate [kg/km]	
v_9: CO_2 emission – manufacturing [kg/km]	
v_{10}: CO_2 emission – disposal [kg/km]	
v_{11}: SO_2 emission rate [kg/km]	
v_{12}: SO_2 emission – manufacturing [kg/km]	
v_{13}: SO_2 emission – disposal [kg/km]	
v_{14}: Mineral rock use – operation [kg/km]	
v_{15}: Mineral rock use – manufacturing [kg/km]	
v_{16}: Mineral rock use – disposal [kg/km]	
v_{17}: Water withdrawal – operation [liter/km]	
v_{18}: Water withdrawal - manufacturing [liter/km]	
v_{19}: Water withdrawal - disposal [liter/km]	

Criteria constitute commonly generated metrics based on vehicle and route/operational parameters. These criteria were taken as inputs to the TOPSIS method. Table 2 presents the set of criteria with their calculation method considering the achieved effect: a positive (benefit criteria) or a negative (cost criteria).

Based on the TOPSIS method [17], the following steps have been defined for the vehicle ranking creation: (1) Decision matrix formation, (2) Matrix standardization, (3) Weighting of the standardized matrix according to the weight of each criterion, (4) Calculation of positive and negative solutions, (5) Evaluation of deviation error, (6) Obtaining of compliance indicator to create the ranking of transport services.

In the TOPSIS method, nine criteria were considered connecting to vehicle ability (consumption/operation) and contamination avoidance (manufacturing/pollution). Such

Table 2. Criteria used in TOPSIS method.

Criteria group	Criteria subgroup	j	c_j criterion	Cost/ benefit	Calculation	Eq.
Vehicle criteria	Traffic dependency	1	c_1: Average speed per trip [km/h]	benefit	$c_1 = \frac{r_1}{r_2}$	(1)
		2	c_2: Traffic congestion relief [-]	benefit	$c_2 = \frac{r_3 \cdot v_1}{v_2 \cdot v_3}$	(2)
	Operation	3	c_3: Energy cost [€/pax]	cost	$c_3 = \frac{v_4 \cdot r_5}{r_4}$	(3)
		4	c_4: Number of trips [-]	benefit	$c_4 = \frac{v_5}{v_4 \cdot r_1}$	(4)
Contamination criteria	Pollution	5	c_5: CO_2eq local emission [kg/(pax · km)]	cost	$c_5 = \frac{v_8+v_9+v_{10}}{r_4}$	(5)
		6	c_6: CO_2eq total emission [kg/(pax · km)]	cost	$c_6 = \frac{v_8+v_9+v_{10}}{r_4}$	(6)
		7	c_7: SO_2 emission [kg/(pax · km)]	cost	$c_7 = \frac{v_{11}+v_{12}+v_{13}}{r_4}$	(7)
	Resources	8	c_8: Mineral rock use [kg/(pax · km)]	cost	$c_8 = \frac{v_{14}+v_{15}+v_{16}}{r_4}$	(8)
		9	c_9: Water withdrawal [liter/(pax · km)]	cost	$c_9 = \frac{v_{17}+v_{18}+v_{19}}{r_4}$	(9)

criteria as local and total vehicle carbon-dioxide (CO_2) emissions, surfur-dioxide (SO_2) emissions, mineral rock use and water withdrawal (required for vehicle construction, operation, and disposal) were also included. The research incorporates vehicle life-cycle analysis.

4 Results

Applying the TOPSIS method, three types of vehicles were considered: buses, taxis and electric scooters. Moreover, two critical parameters were considered: the number of lanes and energy prices in different economic areas (countries). The following lane layouts were distinguished. The arrangement of lanes is shown in parenthesis: 'no. of directions'x('no. of general lanes' + 'no. of bus/combined lanes' + 'no. of cycle lanes'): (A) bus lane (2x(1 + 1 + 0)); (B) combined bus lane, taxis in the bus lane (2x(1 + 1 + 0)); (C) combined bus lane, taxis/bicycle path in the bus lane (2x(1 + 1 + 0)); (D) bus lane, separately bicycle lane (2x(1 + 1 + 1)); (E) combined bus lane, separately bicycle lane (2x(1 + 1 + 1)); (F) bus lane, bicycle road (2x(1 + 1 + 1)); (G) bicycle road (2x(1 + 0 + 1)); (H) nothing: 2x1 lane road (2x(1 + 0 + 0)).

Four cities in four countries were examined as a case study using data from available databases: Berlin, Germany (GER); Budapest, Hungary (HUN); Szczecin, Poland (POL); Stockholm, Sweden (SWE). In each transport mode, three alternative and currently used vehicle fuels were considered: electricity, CNG, and diesel (where it was available). The weights of the criteria were: $w_1 = w_4 = 0.1$, $w_2 = w_3 = 0.15$, $w_5 = 0.3$, $w_6 = w_7 = w_8 = w_9 = 0.05$. The calculation results, presenting rankings created for four countries and eight lane layouts, are shown in Tables 3 and 4.

Table 3. Aggregated result of compliance ranking based on countries.

Countries		GER	HUN	POL	SWE
Bus	Electric	②	②	②	②
	CNG	③	③	③	4
	Diesel	7	6	7	6
Taxi	Electric	4	4	4	③
	CNG	6	7	6	7
	Diesel	5	5	5	5
Scooter	Electric	①	①	①	①

Analysis of the research results (Table 3) reveals that despite its high cost, the scooter is predominantly the best transport option, providing an efficient service for all those who can use it. This is followed by the electric bus and the CNG bus, almost regardless of region. Moreover, in cases with less inclusive infrastructure (A, B, and H) electric buses may be perceived as the most appropriate transport modes (Table 4), while in cases C-G layouts (which indicate a better infrastructure), electric scooters can provide the best service.

Table 4. Aggregated result of compliance ranking based on lane layouts.

Lane layout		A	B	C	D	E	F	G	H
Bus	Electric	①	①	②	②	②	②	②	①
	CNG	②	4	③	③	③	③	③	③
	Diesel	6	7	7	7	7	7	7	7
Taxi	Electric	4	③	4	4	4	4	4	4
	CNG	7	6	6	6	6	6	6	6
	Diesel	5	5	5	5	5	5	5	5
Scooter	Electric	③	②	①	①	①	①	①	②

5 Conclusions

The main contribution of this paper is a comparison and ranking vehicles operated in cities based on the compliance indicator. The presented approach can support the multi-criteria evaluation of different public transport services. Applying the developed method, it was possible to determine the best transport mode considering infrastructure, emissions, and economic criteria based on data regarding Germany, Hungary, Poland, and Sweden. In summary, considering the energy consumption, emissions, and current economic situation, electric buses and scooters are the most suitable means of transport in dense urban environment. It should be mentioned, that energy prices have been heavily weighted and varied considerably in terms of electricity prices from 0.37 (HUN) to 0.88 EUR/kWh (GER) and in terms of emissions from 0.016 (SWE) to 0.8 CO_2eq/kWh (POL). However, electric vehicles are clearly ahead of the competitors as they do not emit local pollution and provide clean and quiet service. This result may be verified for societal group preferences. Our future research will focus on further development of the proposed method considering additional organizational parameters and traffic dynamics. It is recommended to incorporate the presented methodology into the decision-making processes of transport operators in different cities.

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From Shift2Rail to Europe's Rail, Future Perspectives for Alternative Drive Trains Standardizations and Energy Efficiency

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Abstract. Shift2Rail (S2R), railway R&D program, ended in 2023 after several years of works to demonstrate newly technologies to improve railway activities. Inside project PINTA3 on traction system, Work Package 3 (WP3) reports a 1st state of play of alternative drive vehicles in Europe. Since end of 2022, new European program "Europe's Rail" (ERJU) started, with different innovation pillars. One of them, the flagship project 4 "RAIL4EARTH", is focusing on sustainable and green rail systems. Inside RAIL4EARTH, a Work Package, WP01, is working on "Energy Management & Pre-Standardization for Alternative drive trains and related railway system, with the objective to improve standardization and energy efficiency for alternative drive vehicles. Different subtasks in the WP01 will cover the main topics of standardization of interfaces and energy management.

Keywords: Railway · Decarbonization · Standardization

1 Introduction

Since few years, new type of railway rolling stock named "alternative drive" trains have been produced by the industry to decarbonize the railway activities. They are so called alternative because they are an alternative to conventional diesel trains. Diesel trains are producing CO2 and other type of gas such as NOX, contributing to air pollution. In this family of alternative drive trains, we can find the following technologies as explained by Thorne, Amundsen and Sundvor (2020):

- Hybrid combustion engine + battery (using diesel or alternative fuels such as biofuel or HVO)
- Hybrid fuel cell hydrogen + battery
- Full Battery

We can find other type of technologies developed, such as Biogas, but with limited experiences at this time.

Many vehicles are now in service or will be in operation across Europe and in the world as shown by Chamaret, Mannevy, Clément, Ernst and Flerlage (2022). The rise of

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these vehicles could create diverge solutions if no standardization approach is considered in the design. Main risk is to take note of alternative drive trains with high purchasing cost, as well as high operational cost (for maintenance, special devices for inspection, etc.). That's why standardization activities are keys to ensure a better future for alternative drive trains and to offer an affordable technology for all railway community.

In the meantime, since few months, Europe is facing energy crisis costs. In many countries, energy cost increased by third in 2022 compared to 2021, as referred by CER (Community of European Railway and Infrastructure Companies). The grow up of energy prices are pushing railway sectors to drive actions for being more energy efficient. Therefore, development of technologies and solutions to improve energy efficiency, while bringing other values such as reducing maintenance cost, increasing reliability, or minimizing noise emissions are fundamental to support railway as the key backbone of sustainable and reasonable transportation mode.

EU is taking care of railway with financial fundings to bring these expected technologies for low carbon and energy efficient mobility. In 2014, the EU transport council validated the creation of the Shift2Rail (S2R) joint European undertaking. After almost 10 years, S2R is closing the doors of all these activities, with the satisfaction of helping railway to pass a major step and to boost railway industry competitiveness. Whereas this is not the end of the journey, and now EU council regulation established a new initiative for supporting railway in 2021. Named "Europe's Rail Joint Undertaking" (ERJU), this new initiative has the main objective to provide technological and operational solutions to help the railway sector to be the "twin green and digital transition of Europe" as explained by ERJU. The program is based on 7 Flagship Areas (FA) and 1 additional one for transversal topics. One of them, FA4, called "RAIL4EARTH", is focusing on "Green solutions".

2 Shift2Rail Project on Alternative Drive to Diesel "PINTA3 WP3" Outcomes

PINTA is a project from Innovation Pillar 1 (IP1) focusing on traction system improvements, as well as brakes and Heating Ventilation Air Conditioning (HVAC). The project has the main objectives to demonstrate innovative solutions to offer on the market. These new systems will contribute to improve main Key Performance Indicators (KPI) defines in the project, such as energy efficiency, noise reduction, reduction of volume / weight, etc. to obtain a better Life Cycle Cost (LCC) at traction, braking and HVAC level first, but also a train level.

In 2019–2020, the context in Europe and for rail sector to shift diesel trains to low carbon emission technologies, had enforced the PINTA project to be involved on the topic of decarbonization. Therefore, a new Work Package (WP), WP3, has been created with the objective to build a first roadmap on carbon free mobility for railway.

PINTA3's WP3 was separated in 5 tasks, working on Uses cases (task 3.1), Infrastructure (3.2), Operation (3.3), Rolling stock (3.4) and Homologation (3.5). Each task was leaded by a company, with other companies' contributions, to create a collaborative work and approach and for being able to merge the vision on the decarbonization. After roughly 2 years of studies, the 5 tasks have been achieved as followed:

– A census of alternative drive trains in service, in production and ordered have been made to compare the progress on the roadmap for the decarbonization of railway rolling stock in Europe. The Fig. 1 shows the balance between the different kind of alternative drive technologies:
– An analysis of the current infrastructures and their limits with impacts on alternative drive trains in operation. This study helps to evaluate the evolution to proceed in the future for improving the charging of batteries or hydrogen, as well as looking for more standardized charging process,
– The definition of common requirements between France (SNCF) and Ger-many (DB) for alternative drive trains in terms of operation for merging the needs and so, evaluate the needs for alternative drive trains characteristics.
– An analysis of the current alternative drive trains performances at rolling stock level and at Energy Storage System (ESS) level, to compare with needs for gap analysis,
– Collecting the feedback from commissioning process and on standards used for checking the design of ESS. Then, identification of regulations and standards to develop/modify,
– Research on train architectures to improve availability of alternative drive trains in degraded modes and to improve performance.

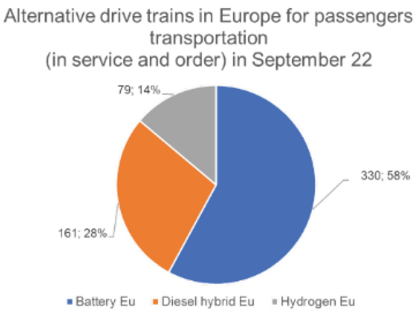

Fig. 1. Alternative drive technologies in Europe for passenger

All these works have been inputs for ERJU "RAIL4EARTH" objectives to close the gaps for supporting alternative drive trains expansion in Europe. It's also giving new perspectives for catenary lines trains to be able to face off climate changes and energy crisis (e.g. reused ESS's technology development for alternative drive trains on electric catenary trains for back-up in case of electrical failures on the power supply side).

3 Europe's Rail JU Project on Decarbonization and Energy Efficiency of Railway System "RAIL4EARTH WP01"

3.1 General Presentation

Since end of 2022, new European program "Europe's Rail" (ERJU) started, with different innovation pillars. One of them, the flagship project 4 "RAIL4EARTH", is focusing on sustainable and green rail systems, but also on noise and vibration reduction, circular economy, resilience to climate change and attractiveness. This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No: 101101917. A mix of European countries will work altogether to target the improvement the existing sustainability performance of railways, building a more attractive and resilient transport mode and contributing to-wards the objectives of a climate neutral Europe for 2050.

Especially, WP01 on "Energy Management & Pre-Standardization for Alternative drive trains and related railway system", is one of the WPs working on improving standardization and energy efficiency for alternative drive vehicles. The main objectives of WP01 are:

- Development of optimize energy management between rolling stock, infra-structure, and operation,
- Improving the control and management of energy at system levels, between railway and power grid,
- Energy management with the standardization of eco-mode functions on-board of rolling stock,
- Pre-standardization and interoperable interfaces between train and infrastructure and operation.

These goals shall contribute to the main KPIs of RAIL4EARTH, which are physical energy consumption, physical CO2 equivalent emissions, LCC reduction and increasing range for battery trains (target 200 km). WP01 established 2 tasks, task 1.1 on "Pre-Standardization for Trains with Alternative Drives", and task 1.2 on "Smart Energy Management".

3.2 Pre-Standardization for Trains with Alternative Drives (RAIL4EARTH WP01 Task 1.1)

In task 1.1, we are identifying the different interfaces for alternative drive trains. For example, interface of traction batteries with rolling stock. In a first step, a state of the play of current and ongoing projects with traction batteries will be done. Based on partners involved, the group is representing around 460 alternative drive trains in Europe. In a second step, we propose standardized design of batteries interfaces. We defined the interfaces at Energy Storage Unit level (ESU), according to IEC 62498 standard. Interface types are electrical, mechanical and communication. Discussions are ongoing to create as much as possible standardized parameters to improve the interoperability of the batteries between alternative drive vehicles, as well as reducing the cost of production and improved maintainability during operation.

We worked also on the interfaces between alternative drive trains and infrastructure.

Concerning battery train interfaces, we started to work on the topic of fast charging. First, fast charging process can involve additional modification at different level of the subsystems on infrastructure side to reinforce for supporting high power charging requested (power of the transmission post, as well for transformer and rectifier in substation, sizing of the overhead line or of the return circuit, etc.). Clearly, exchange between infrastructure manager and train operators is key to clarify the power demand for battery trains charging. Special condition to activate the fast charging should be evaluated as well, such as communication between train and infrastructure (rolling stock send charging profile request to infrastructure, infrastructure reply by approving the demand, charging process starts).

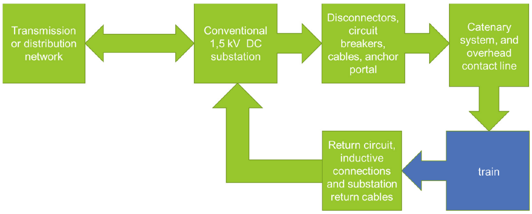

Fig. 2. Blocks diagram of energy conversion charging from infrastructure view

Future works will be focus also for hydrogen refueling as well, because it is a key issue to standardize for reducing the cost of refueling station for hydrogen.

3.3 Smart Energy Management (RAIL4EARTH WP01 Task 1.2)

Concerning subtask 1.2.1 (pre-standardization of energy management functions), we started first by identifying the different kind of energy functions on-board rolling stock and on-ground.

About subtask 1.2.2 (smart energy management), we used the data from other WPs (5 and 6 for battery trains) to evaluate different energy management strategies to optimize energy consumption. Different partners and countries have selected use cases to compare the benefits from 1st generation battery trains (roughly 80 km range) to future 2nd generation battery trains with expected 200 km range in operation. The Fig. 2 is presenting the analysis done for 1 case in France:

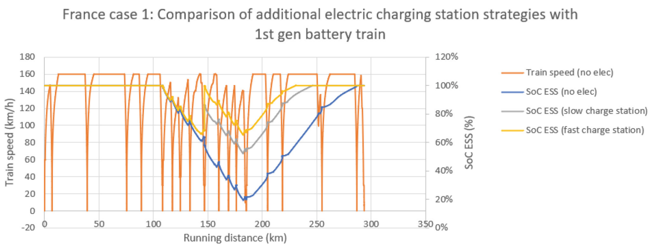

Fig. 3. Comparison of a BEMU 1st generation with different partial electrification strategies

Without any additional infrastructure, the Deep of Discharge (DoD) of the State of Charge (SoC) is very important (−80%). This value will have impact on ESS design and battery lifetime for rolling stock side, but especially, from operational side, this gives low margin in case of any disturbance on the line. To reduce this risk, a possible way is to install new infrastructure for charging the batteries. Based on the railway line characteristics and schedules, we took the assumption to evaluate the advantages of a charging station at the end station todays not electrified. We created 2 type of charging station, a first one "slow-charge" and a second one "fast-charge". Slow charge station can deliver up to 450 kW at catenary, and for Fast charging one can go up to 1500 kW. Thanks to this strategy, the DoD can be reduced till − 48% (slow charge station) and − 35% (fast charge station). Whereas investment on infrastructure side should be com-pared with improvements on rolling stock side, such as in similar studies done by VDE association (2018). Development of next generation on-board ESS are ongoing in WP05 in RAIL4EARTH project, with objectives to improve battery performances. Other developments inside RAIL4EARTH, such as energy management functions or aerodynamics will help also to reduce energy consumption and, in the meantime, in-crease the range in operation. These improvements will be simulated separately to evaluate the benefits on different scenarios (Fig. 3).

4 Conclusion and Future Works

Railway decarbonization is on a good shape by announcing more and more sustainable alternative drive trains in Europe. This is consistent with the agreements across Europe to be carbon free for railway operation. S2R PINTA3 WP3 helped to give a first vision on how decarbonization is progressing in Europe and what are the key developments to follow up. ERJU RAIL4EARTH WP01 works are contributing to support the development of alternative drive trains, by addressing the items identify in S2R. With more standardized alternative drive trains, we will support an affordable cost of energy efficient and sustainable solutions for rail sector. Additionally, technical studies for smart energy management also helps to recommend optimized scenarios in terms of LCC. Currently, the studies and works of WP01 are still ongoing until the end of the phase 1 in end of 2026. Complementary works in WP05 & 06 on long-range battery trains development will bring important inputs for supporting the WP01 studies.

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The Life4MEDECA Knowledge Centre: An Interactive Thesaurus for the MEDECA Implementation

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Abstract. The Mediterranean countries during COP22 agreed to designate an Emission Control Area for sulfur emissions, the MEDSECA which, according to the International Maritime Organization (IMO), come into force in 2025. The countries also agreed to work on nitrogen oxide (NO_x) emissions in the next two years to bring forward a NECA marking a significant step forward towards cleaner air in the whole basin.

In this contest, the LIFE4MEDECA project aim to support the establishment of MEDECA by sharing knowledge following quintuple innovation helix approach, identifying gaps and needs for its implementation, analyzing the economic, environmental and social impact of fuel switch, and the most appropriate tools and policies to alleviate the related costs.

The legacy and knowledge gathered by the LIFE4MEDECA project create a kind of thesaurus of ECA documentation, which has been collected in the Knowledge Centre - KC, a tool for strengthening the technical, legal and financial capacities of EU and non-EU Mediterranean countries to comply with ECA requirements, to support local implementation and to increase awareness.

An interactive online platform has been developed which enables the acquisition of information on different topics and aspects concerning the implementation and enforcement of the MEDSECA, by means of technical documentation, articles, relevant data, webinars, courses and interviews provided by experts and opinion leaders.

The KC aims to homogenize the available fragmented information, support information exchange with experts in fields, and give appropriate training for example for the specific topic related to research and technology development.

Keywords: Emission Control Area (ECA) · Shipping · Mediterranean · Emissions · Capacity building · Innovative technologies

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1 Needs for the MEDECA Implementation

The LIFE4MEDECA is a preparatory project (January 2021 - December 2023) aims to build consensus and awareness on the creation of an area with low emissions of atmospheric pollutants in the Mediterranean Sea, the MEDECA (i.e.: Mediterranean Emission Controlled Area).

Since at the IMO meeting in December 2022, together with the formal decision on the effective date of MEDSECA (i.e.: Emission Controlled Area for SOx, May 2025), the countries also agreed to work on nitrogen oxide (NOx) emissions in the next two years, LIFE4MEDECA has expanded its initial objectives to support the establishment of both SECA and the possible NECA in the Mediterranean.

To support stakeholders and authorities in enforcing the MEDECA decision, a dedicated Knowledge Centre for sharing knowledge and best practices is being developed and will be soon fully operational. The Knowledge Centre will be the "LIFE4MEDECA heritage" and be continued after its completion according to the "after LIFE" continuation plan, so as not to lose the knowledge gathered and to allow for future updating. It is important to emphasize that in the light of the IMO decision, it is crucial to continue technical and legal capacity building and to further develop contents at a multidisciplinary level i.e. technical, legal, institutional, economic, infrastructural, procedural, and financial.

The LIFE4MEDECA Knowledge Centre not only ensures that diffused information on the establishment of the SECA is consolidated into a comprehensive multilingual platform but also provides updated information on the NECA and, along different time horizons, on air quality impacting on human health, on greenhouse gas emissions, and on the sustainability of shipping in general.

The capacity building tools should help answer one or more of the following questions, according to the needs of the target audience to be addressed: how to face the transformation, how to pioneer, to govern, to finance, to enforce the transformation.

This capacity building tool will also be a pillar for experimentation-based collective learning, as it will help formalize and share the knowledge coming from experiences by the operators located in different territory, in exploring the issues related to the ECA establishment at local level according to their specific vocation and specialization. Following the principles for environmental regulation in shipping, based on a polycentric approach, as suggested by the literature on polycentric climate governance, a multilateral approach is actually encouraged in this respect, given that key factors that make polycentric approaches effective are the opportunity for experimentation and policy learning [1].

Given the heterogeneity of the Mediterranean socially, politically, and economically, this approach allowed to assess appropriate tools to address regional differences, differentiating policy approaches and technological solutions.

With regard to naval emissions, a more restrictive uniform regulation at a global level (i.e. a new "IMO standard", applicable without distinction to the high seas, straits, territorial waters) has implications on infrastructural assets, facilities, services that cannot be foreseen. Notably, it is not clear "who pays for what" and what effects this regulation could have on the shipping market structure, on the choices of shipowners operating vessels under different flags, on the port industry (routes and ports of call change, and how do they change?). Such uncertainty is amplified by the presence of technological solutions available over different time horizons, capable of impacting on costs/benefits. In this perspective, recipient countries can benefit and be more easily persuaded from the gathering of experiences, data, evidence, and in the meanwhile, it is easier to develop and prove concepts in 'test' areas before scaling them up [2]. ECAs regulation at a local level eventually results in an experimentation-based approach to enforcement of an innovative legislation, i.e. after testing on a larger scale, this activates a collective learning process to define a uniform regulation at a global level towards enforcement of ECAs designated under Annex VI of the MARPOL Convention. For these reasons, the need arises to create a collective tool that fills the scientific, technological, and policy gaps on issues of fundamental relevance to the implementation of a MEDSECA.

2 The Knowledge Centre Structure

The structural framework of the LIFE4MEDECA Knowledge Centre, KC, is composed of *(i)* a repository containing documents, data, videos, policies, and similar materials; *(ii)* a selection of capacity-building tools, accessible through drop-down menus and *(iii)* the provision for users to curate their customized set of capacity-building tools. Access to the Knowledge Center will be facilitated through a user-friendly web interface, enabling interested and profiled users to navigate through predefined paths selected by *Topic* (based on the 8 LIFE4MEDECA scenarios), *User type* (e.g., competent authority, policy maker, R&D performer, infrastructure owner, etc.), *Country*, and *Task/Goal* (preparedness, deployment, promotion, financing, or enforcement).

The structure of the KC (Fig. 1), which takes inspiration by past similar tools [3, 4] built within the framework of EU initiatives, retraces the process developed during the LIFE4MEDECA project. The background knowledge on which the repository is based is a collection of experiences that establishes a contextual framework and serves as a key resource for the following steps [5]. The central section "Experiences of other ECAs" collects evidence and information from the Baltic, North Sea, and North American ECAs [6]. This segment serves as a comprehensive repository for documents, studies, and other relevant content regarding the implementation, enforcement, and post-creation phases of ECAs as inspiration for the MEDECA process. Moreover, the "MEDECA Studies and Preliminary Measurements" section summarizes studies conducted by external agencies and official documents from REMPEC and IMO on the status of the MED-ECA [7–9]. Air quality measurements conducted during the project in major Mediterranean ports (i.e., Barcelona, Malta, Livorno, Civitavecchia, etc.) are also reported, accompanied by links to data from Italian and Mediterranean stations as well as EMSA [10]. This database of global and local air quality measurements can be the reference for future evaluation of the benefits of the MEDECA.

The core of the KC resides in the capacity building section, where technical and strategic knowledge pertinent to ECA development is systematically cultivated. Within this framework, principal *scenarios* have been identified i.e., macro-themes that will play a significant role in the implementation of the MEDECA in relation to the evolving technological, economic, legislative, and regulatory developments that will occur between now and 2025 and then 2030. In the process of identifying scenarios, it was also considered to include the effects of the MEDECA on the marine and coastal environment

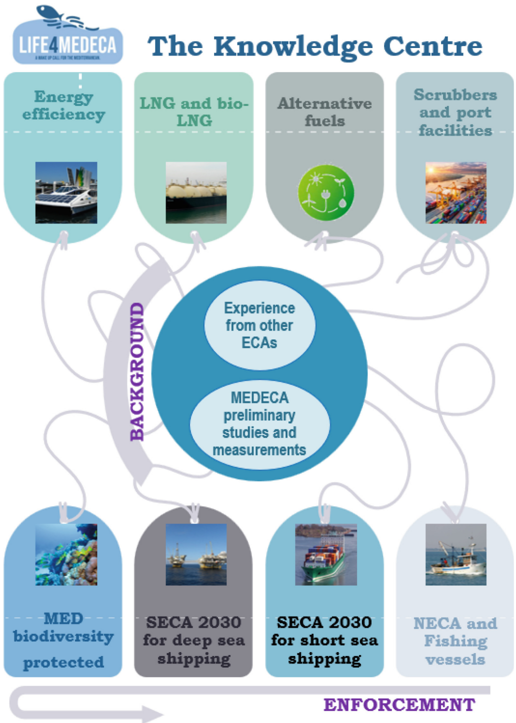

Fig. 1. The Knowledge Centre – KC structure. Source: Authors

and the possible entry into force of the MEDNECA (i.e.: Emission Controlled Area for NOx). Successfully preparing for and promoting the materialization of each scenario necessitates the cultivation of capacities that may not currently exist in every country or organization. The KC's capacity building process aims to offer this knowledge with respect to the main issues, *i.e.* SECA 2030 Short Sea Shipping, SECA 2030 Deep Sea Shipping, LNG & Bio-LNG, NECA Compliant MED Fishing Boats, Energy Efficiency, Alternative Fuels Other Than Carbon, MED Biodiversity Protected.

For each scenario, capacity building tools (training session, further reading material, videos, datasheet, info and link to relevant documents) should be provided/foreseen for:

i. generic audience in this case a sort of "self-service" menu could be provided where the user selects what wants to browse/see among all the tools provided for the specific scenario;
ii. specific audience according to the above categories, namely: National and/or Local Competent Authority; Port and/or national/local agency; R&D sector; Operator (maritime, logistics, tourism, etc.); Owner (of ships, infrastructures, related service companies, etc.); Decision Maker other than competent authority, port or agency; Target Country; other EU or non-EU Countries;
iii. for each specific audience, the scope (hence the contents) of the capacity building tools should help answering one or more of the following questions: i) how to face the

transformation (preparedness), ii) how to pioneer the transformation (deploy/comply with/fulfil), iii) how to govern the transformation (drive, promote, lead), iv) how to finance the transformation and v) how to enforce the transformation (ensure/verify compliance);

Each scenario is related to a different aspect (research, authority, economy) and therefore developed in a way adaptable to the scope. Just to give an example, the R&D scenario on energy efficiency was entirely developed as a course whose lectures by researchers who are experts in the field illustrate the main technological solutions for reducing ship emissions.

A final and key KC's section will cover the monitoring and updating of the repository in the future after ECA-life when will be implemented, ensuring the fundamental *enforcement* process.

3 Conclusions

In an "after LIFE" future perspective, this Knowledge Centre will be yearly updated and improved with further tools, such as a handbook for decision support aimed at providing a guide for Port managers to take strategic investment decisions, to prepare the necessary port facilities-infrastructures-assets for matching the requirements of the Emission Control Area. The KC interactive tool will give the possibility to assess the most financially viable solution to comply with the ECA's requirements working as a so-called THECA, sort of a thesaurus of ECA documentation, and an advanced stakeholder assessment. The contents of the KC can be used to support the implementation of future ECAs (e.g., the Atlantic ECA) and its structure is suited to host the knowledge and tools that will be developed for and within future ECAs. The goodness and usefulness of the platform will be evaluated by specific defined indices, such as the number of active users, participations in interactive thematic forums, and requests for active participation in the creation of new content. This will clearly be critical in evaluating the continued use of the platform or any adjustments to it.

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Thermal Management of Double-side Cooled SiC MOSFET Power Modules for Lifetime Enhancement of Automotive Applications

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Abstract. The rise of electric vehicles (EVs), driven by environmental concerns and increasing consumer demand, presents challenges such as reducing charging times, extending range, and ensuring reliability. Innovations in power electronics provide solutions for faster charging and enhanced efficiency but generate more heat in smaller volumes, necessitating efficient thermal management. This study investigates various cold plate designs for double-side cooled (DSC) SiC MOSFET power modules in high-power EV traction inverters. The performance of these designs is evaluated through lifetime assessments and thermal analyses, employing Computational Fluid Dynamics (CFD) simulations across a range of conditions.

Keywords: Thermal Management · Lifetime Assessment · DSC Module · SiC MOSFET · CFD Simulations · Electric Vehicle

1 Introduction

The adoption of zero-emission mobility has gained momentum with the announcement of a new regulation by the European Council, mandating that all new cars and vans registered in the European Union are set to be zero-emission from 2035 [1]. However, electric vehicles (EVs) still face challenges such as reducing charging time, increasing travel range, and fulfilling service target lifetime to be more competitive [2]. Innovations in power electronics offer solutions and promise faster charging, heightened efficiency, and reduced component size and weight. Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) have emerged as a prominent alternative to conventional silicon-based power modules in traction inverters as they offer reduced conduction losses, lower on-resistance, rapid switching capabilities, higher breakdown voltage, extended temperature ranges and cost-effectiveness [3]. These

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advancements in power electronics, however, necessitate efficient cooling systems to maintain junction temperatures within prescribed limits, such as a junction temperature. Liquid cooling, renowned for superior thermal performance, particularly shines in automotive applications as a top solution. Adding structures like pin-fins, ribbons, or microchannels enhances liquid cooling, further improving heat transfer efficiency by increasing the heat transfer area [4]. This study investigates various cold plate designs for double-side cooled (DSC) SiC MOSFET modules in automotive traction inverters. It aims to assess different cooling configurations, including single-sided and double-sided setups, as well as their microchannel versions. Computational Fluid Dynamics (CFD) simulations in Ansys Fluent have been employed to evaluate thermal behavior, pressure distribution, and flow patterns, considering parameters such as flow rate and coolant temperature. Furthermore, the impact of various cold plate designs on the module's lifetime has been explored using the standard Arrhenius equation.

2 Cooling Design

Double-sided aluminium cold plates play a critical role in EV traction inverters by effectively dissipating heat generated during power conversion. Constructed with a focus on temperature management, performance optimization, and malfunction prevention, these aluminium cold plates boast excellent thermal conductivity. This feature is particularly beneficial in ensuring the efficiency of EV traction inverters. Cold plate design varies significantly based on thermal and reliability requirements, involving the configuration of a cooling system that efficiently dissipates heat while meeting stringent thermal and reliability criteria.

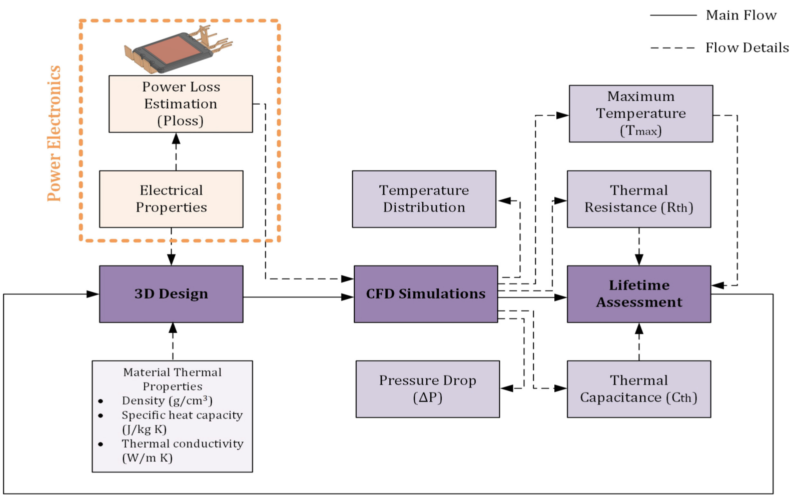


Fig. 1. Flowchart of the cold plate design cycle.

This study's cold plate design cycle, shown in Fig. 1, takes a multifaceted approach to evaluate how thermal design impacts power electronics system longevity and performance. The aim is to enhance reliability and thermal efficiency through optimized cold plate designs while minimizing coolant pressure drop. In this study, four distinct aluminium cold plate designs, drawn in Fig. 2, are designed to address specific thermal management requirements for three DSC SiC MOSFET modules.

- Design 1 (DN1) - Single-sided cooling: A single plate beneath SiC MOSFETs enhances one-sided heat dissipation.
- Design 2 (DN2) - Single-sided cooling with microchannels: Microchannels added to the plate beneath SiC MOSFETs optimize heat transfer.
- Design 3 (DN3) - Double-sided cooling: Two plates, one at the bottom and one at the top of SiC MOSFETs, ensure comprehensive cooling.
- Design 4 (DN4) - Double-sided cooling with microchannels: Combining double-sided cooling with microchannels on both sides.

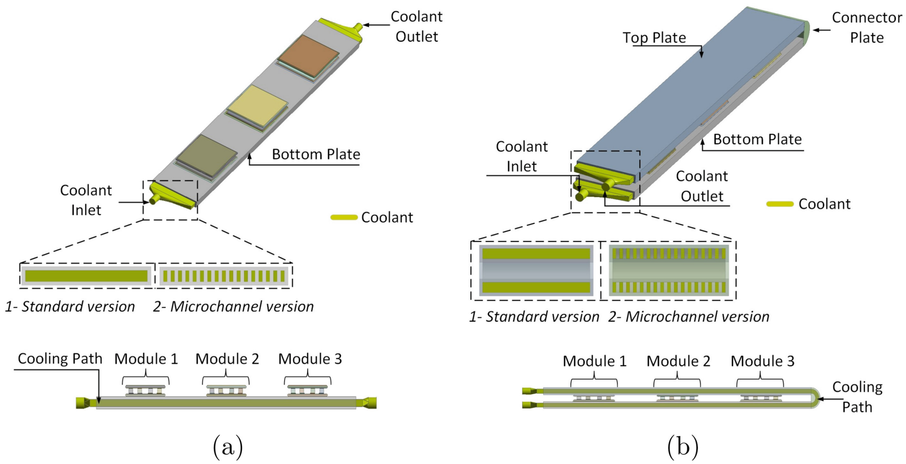


Fig. 2. Cold plate designs: (a) single-sided, (b) double-sided.

3 CFD Simulations

CFD simulations have been performed using Ansys Fluent to assess the thermal performance of the designed cold plates in this study. These simulations have focused on evaluating forced liquid cooling's effectiveness by circulating water through the aluminium cold plate to dissipate heat generated by the SiC MOSFET chips.

Various conditions have been explored, including different coolant inlet temperatures (25 °C and 65 °C) and flow rates (2 to 12 L/min), providing insights into heat dissipation and thermal uniformity. Heat loss per chip considered switching and conduction losses of SiC MOSFETs by simplified models, based on manufacturers' datasheet parameters. A total heat loss of 1800W for the three modules was calculated. The simulations, refined under steady-state conditions, have produced results in Fig. 3 for an inlet temperature of 25 °C. DN4, featuring double-sided cooling with microchannels, excels in thermal performance. Conversely, DN1, featuring single-sided cooling, exhibits poorer thermal performance, resulting in higher temperatures. DN4's superior thermal control comes with a higher pressure drop, while DN1 experiences the lowest pressure drop. Despite a significant increase in pressure drop, DN4 sustains a narrower temperature difference (approximately 10 °C) across various flow rates. This allows to use of DN4 at reduced flow rates.

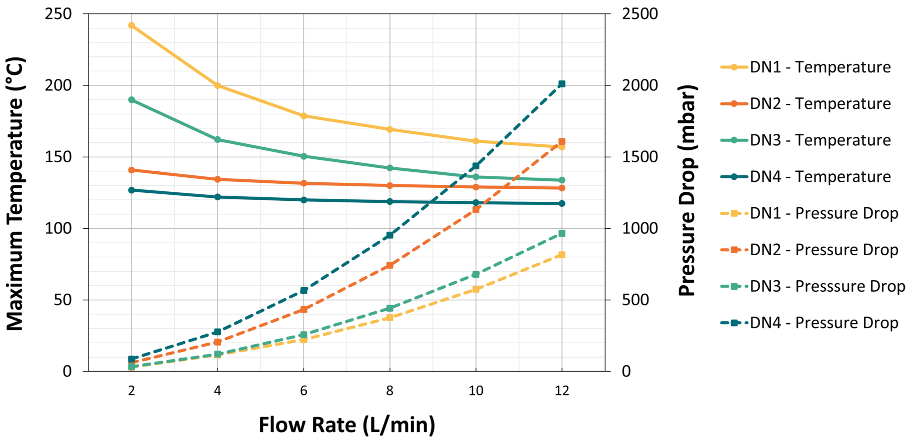
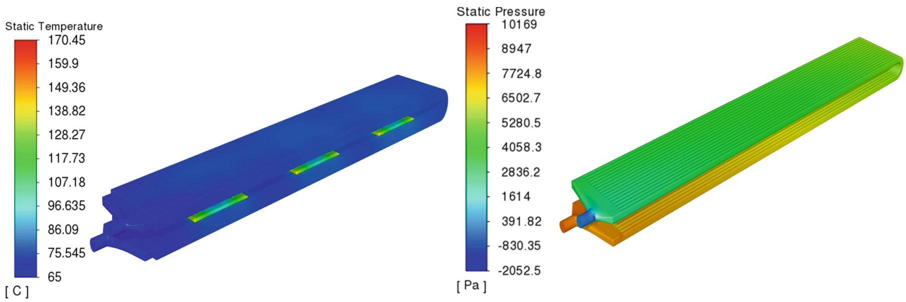


Fig. 3. Temperature on the chips and coolant's pressure drop results.



(a) (b)

Fig. 4. CFD simulation results: (a) temperature distribution of the whole system, (b) pressure drop of the coolant.

Further CFD simulations have been conducted to assess thermal performance of DN4 under extreme simulation conditions: a coolant inlet temperature of 65 °C, a flow rate of 2 L/min, and a constant total system heat loss of 1800 W. The extreme simulation condition resulted, as shown in Fig. 4, in a pressure drop of 122 mbar and a maximum temperature of 170.5 °C, successfully maintaining the chip's junction temperature below its functional limit of 175 °C with less pressure drop.

4 Lifetime Assessment

This section assesses the lifetime of the traction inverter using SiC modules with designed cold plates, where the standard LESIT parameters (Equation (1)) are used [5]. Here, an 80 °C constant junction temperature fluctuation (ΔT_j) is considered, and the maximum junction temperature at the 8 L/min flow rate is replaced with T_m. Figure 5 shows the number of cycles to failure impact of the cold plate designs on the inverter lifetime.

$$N_f = a \times (\Delta T_j)^{-n} \times e^{\frac{E_a}{K_b \times T_m}} \tag{1}$$

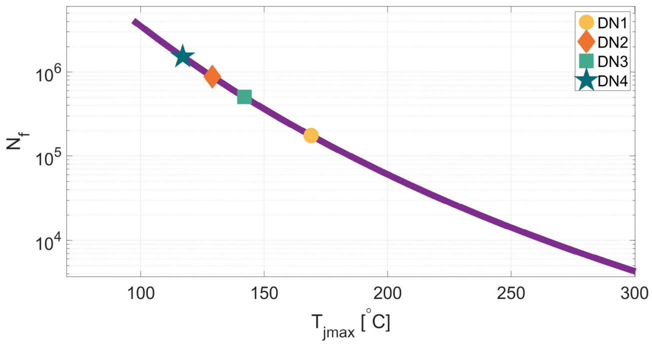


Fig. 5. Comparison of N_f for variable T_m for $\Delta T_j = 80°$C.

5 Conclusion

This study employs CFD simulations to comprehensively assess the thermal performance of various cold plate designs for the lifetime enhancement of high-power EV traction inverters. Different simulation conditions are explored, shedding light on both heat dissipation and uniformity. In terms of thermal performance and reliability, DN4, characterized by double-sided cooling with microchannels, stands out by maintaining the lowest maximum temperature and extending the lifetime of components. Remarkably, it exhibits approximately nine (9) times fewer failure cycles compared to DN1. Further simulations under extreme conditions confirm DN4's ability to maintain the chip's maximum junction temperature below 175 °C, ensuring optimal functionality and system reliability.

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Active Travel Infrastructure (ATI) in Ireland – An Asset Management Approach

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Abstract. Ireland is committed to boosting active travel as a key part of its decarbonisation plan. The development of Active Travel Infrastructure (ATI) which facilitates walking, cycling, and other non-motorised forms of transportation, is a focal area of Ireland's substantial capital investment efforts aimed at advancing its sustainable transportation goals. While investing in the new ATI, the aspect of ongoing maintenance and renewal is frequently overlooked. However, to ensure the realisation of the benefits of active travel, it is essential to have a sustainable asset management system accompanied by sufficient funding to uphold a consistent level of service throughout the infrastructure's lifespan. This paper highlights the importance of a systematic management, maintenance, and renewal strategy for ATI assets that includes planned asset renewal, routine maintenance activities, and winter operations. It also proposes the funding requirements for maintaining and preserving the lifespan of existing and new ATI.

Keywords: Active Travel Infrastructure · Asset Management · Transport Infrastructure Ireland · National Cycle Network · Greenways · Footways

1 Introduction and Background

1.1 Policy Context

Ireland has pledged to achieve a 51% reduction in carbon emissions by 2030; increasing active travel as part of a move to more sustainable transport is a vital element to achieving this reduction. The National Sustainability Mobility Policy sets out an ambitious target to deliver at least 500,000 additional daily active travel and public transport journeys and a 10% reduction in kilometres driven by fossil-fueled cars by 2030 [1]. In pursuit of these targets, Ireland is making significant investments in Active Travel Infrastructure (ATI) including all types of pedestrian and cycle facilities that improve conditions for people walking, wheeling, and cycling.

Aligned with the National Sustainability Mobility Policy and National Development Plan [2], the Department of Transport developed The National Investment Framework

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for Transport in Ireland (NIFTI) in 2021 [3], which sets out a framework for prioritising future investment in transport through 2040, acknowledges the vital role of active travel to achieving these objectives.

The NIFTI framework positions active travel at the top of the ‘Modal Hierarchy’, prioritised above public transport and private vehicles. The framework also proposes an ‘Intervention Hierarchy’ with investment in maintenance prioritised above optimising and improving existing infrastructure, and the provision of new infrastructure. Considering these two hierarchies together highlights the key role of maintenance in encouraging active travel (as seen in Fig. 1).

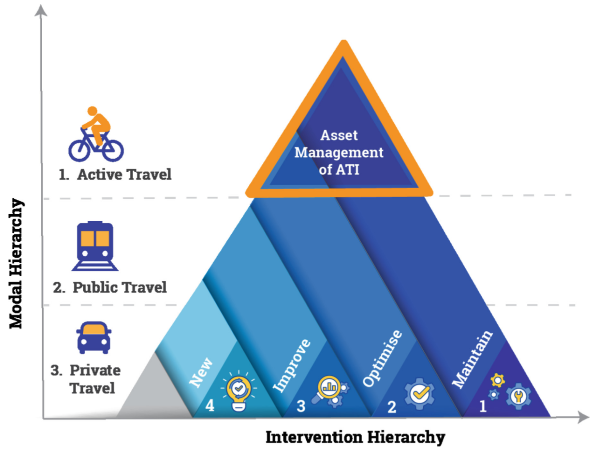

Fig. 1. NIFTI Modal and Intervention Hierarchies and the Role of Asset Management of ATI (Image produced by Authors).

The Transport Infrastructure Ireland (TII) publication National Roads – Active Travel Planning [4] details six principles for ATI planning and design. These principles state that such infrastructure should be: Inclusive; Safe; Connected; Direct; Legible; and Attractive and Comfortable.

1.2 ATI in Ireland

TII is currently responsible for c.800 km of footways and c.900 km of cycleways. In addition, since 2021, TII has been responsible for the approval of c.600 km of new Greenways, with a significant number in various stages of planning and construction.

1.3 Planned Development of the ATI Network

Greenways. Greenways are recreational or pedestrian corridors for non-motorised journeys, developed to enhance both the environment and quality of life of the surrounding area [5]. From 2021, €60M of capital funding has been allocated annually for the delivery of new Greenways with a total of 2,600km planned. These include trailheads, car parks and other facilities. The majority of the planned Greenways corridors are on existing infrastructure that is owned by third parties and more than 50% are on infrastructure owned by Irish Rail, the vast majority of which are disused railway lines.

As well as the cycleways themselves, this existing infrastructure is estimated to include up to between 1,000 and 1,500 bridges. These bridges will require ongoing routine inspection and maintenance as well as potential upgrades and rehabilitation to bring them to an appropriate level of safety and serviceability for their use on the Greenways network.

National Cycle Network. The aim of the National Cycle Network (NCN) is to link towns, cities, and destinations across Ireland with a safe, connected and inviting cycle network, encouraging people to cycle rather than drive [5]. Once complete, the NCN will comprise some 3,500km of new and existing cycleways, incorporating Greenways, integrated and segregated cycle lanes, as well as repurposed infrastructure owned by third parties.

The continued development of Greenways, as well as the planned NCN, will eventually triple the total length of ATI network that will need to be maintained and renewed as shown in Fig. 2.

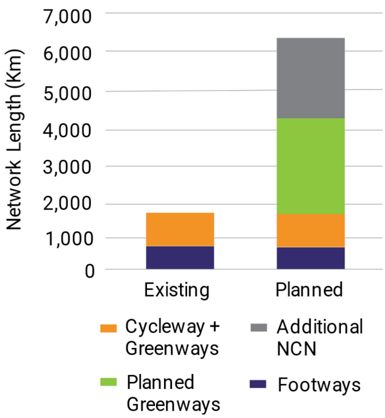

Fig. 2. Future Extent of ATI.

2 Asset Management of ATI

2.1 The Importance of Asset Management to Achieving the Long-Term Benefits of Active Travel

Ongoing maintenance and renewal are often overlooked when investing in ATI, but users and potential users of those networks repeatedly indicate that asset condition is a key factor in deciding whether to walk or cycle [6]. Regardless of how well the new ATI is built, unless it is maintained to a consistent level of service over the whole life of the infrastructure, it will inevitably be underutilised.

Key to the ongoing realisation of the benefits of active travel is, therefore, the establishment of a systematic asset management regime, supported by adequate funding and resources.

2.2 Current Approach to Asset Management of ATI

The majority of existing ATI is maintained on TII's behalf by Local Authorities as part of their annual Ordinary Maintenance allocation while the rest are maintained by the Motorway Maintenance and Renewal Contract (MMaRC) operators.

The current approach to the asset management of ATI is primarily reactive; no planned maintenance or renewal is carried out except as part of adjacent carriageway renewal or safety schemes. There is a lack of common maintenance standards, which coupled with the lack of consistent methods of assessing asset condition, makes it difficult to develop and prioritise forward maintenance programmes and budgets with any degree of confidence. Moreover, the specific maintenance needs of cycleways are not defined for national roads.

2.3 Maturing TIIs Approach to Asset Management of ATI

Given the increased importance of active travel and the significant planned increase in ATI in Ireland, a more proactive and systematic approach to its maintenance and renewal will be needed. This will require several key elements to be implemented as shown in Table 1.

Table 1. Asset Management System Elements

Asset Management System Element	Description
Roles & Responsibilities	Define clear roles and responsibilities for asset management functions and liabilities, especially for assets that are currently owned by third parties
Network Definition	Reliable and consistent data is required about the location and importance of the infrastructure, including a common location referencing system, and hierarchy that enables investment to be prioritised on a consistent basis across the network
Inventory Data	Reliable information is needed about the age and construction of the infrastructure
Maintenance and Standards	Common maintenance standards are needed that reflect the priorities of users and deliver an appropriate level of service, including during winter months
Condition Assessment	An appropriate, condition survey regime is required that enables long-term maintenance management decisions

(*continued*)

Table 1. (*continued*)

Asset Management System Element	Description
Programme Development	Appropriate methods should be developed to identify and prioritise planned maintenance schemes
Lifecycle Modelling	Lifecycle modelling capability will support the identification of future funding needs, including the impact of different funding levels
Funding and Resources	Adequate funding and resources are needed that cover reactive and cyclical maintenance including inspections, asset renewal and winter service
Performance Monitoring	Performance Indicators (PIs) should be developed to allow the effectiveness of the management of ATI to be monitored and controlled in line with TII's overall asset management objectives

If changes are not made to the approach to the management of ATI assets, there is a risk that the network will deteriorate over time to the point where users are discouraged from using it, the benefits will no longer be achieved and ultimately the costs of restoring serviceability will be much higher.

2.4 Impact on Funding

While some of the expanded network of ATI will be newly constructed, much will comprise existing assets, including bridges and other assets, of varying age and conditions. These existing assets will require maintenance and renewal within a relatively short timeframe. Additionally, the newly constructed infrastructure will require renewal in the longer term and ongoing routine maintenance and winter service throughout their operational lives.

Based on the planned development of the Greenway network, it is estimated that, the cost of routine maintenance of ATI, excluding structures, could increase by up to €6.9M per year and that, over the longer term, for every 100km of ATI constructed, an additional €1.2M could be required each year for capital renewal.

In addition, it is estimated that the costs of inspections and routine maintenance of bridges could increase by up to €1.1M per year with up to €1.4M per year additional funding required for capital renewal. Beyond that, it is estimated that every 100km of further extension of the ATI network could increase inspection and routine maintenance costs for structures by up to €250K per year and capital renewal by up to €250K per year.

3 Conclusion and Future Development

The current approach taken to the maintenance of ATI has been appropriate given the nature and extent of existing footways and cycleways. However, with active travel's increased priority and the significant investment in new active travel infrastructure, it is vital that a more systematic and proactive approach is taken to the management of these assets in the future.

The adoption of an asset management approach, supported by adequate funding and resources, will ensure that the investment in new infrastructure is protected over the long term and that ATI continues to meet the needs of users throughout its life, for the benefit of all.

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Bicycle Traffic Analysis Before and After Mobility Interventions Using Crowdsourced Data

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Abstract. This paper aims to investigate the impact of a new cycleway on Panepistimiou st., implementing in the framework of Athens Great Walk (AGW), to bike and e-bike trips using crowdsourcing open data, which are paired with the original data of the Horizon Europe project PHOEBE. For this purpose, daily cycling trips recorded on the examined street before and after the operation of the new cycleway, were collected through "Strava Metro" platform. An interrupted time series analysis was developed to assess the effectiveness of the new cycleway on Panepistimiou st. on daily changes in number of bike trips from June 2019 to 2023. The Covid-19 pandemic lockdowns are regarded as supplementary interruptions due to their documented impact on inducing temporary and significant shifts in cycling patterns. Evaluation of the post-intervention period show an increase in cycling subsequent to the introduction of exclusive lanes for cyclists and widened sidewalks under AGW.

Keywords: PHOEBE · Interrupted Time-Series · STRAVA · Cycling · Athens Great Walk · COVID-19

1 Introduction

Urban centres worldwide are grappling with mounting issues caused by motorized road transport. In light of this reality, cities face the challenge to enhance the quality of urban environment promoting sustainable transport modes such as bicycles [1]. Creating bicycle paths and expanding sidewalks to allocate road space for active travel modes emerge as fundamental measures for promoting sustainable mobility and addressing the external costs associated with transportation [2]. In line with these efforts, numerous cities have implemented sustainable urban transport policies, resulting in notable shifts toward active mobility and enhanced road safety.

Following the lead of numerous cities globally, Athens implemented several impactful mobility interventions in June 2020 formed a major urban regeneration plan titled the Athens Great Walk (AGW). The objective of these interventions was to create a new quality environment of urban mobility, promoting public transport and active travel modes,

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to achieve safe, green and efficient transport for all. Noteworthy interventions included expanding sidewalks on streets with high pedestrian traffic and creating dedicated lanes exclusively for pedestrians and cyclists.

The PHOEBE project ("Predictive Approaches for Safer Urban Environment") was initiated to enhance road safety for vulnerable road users, particularly those utilizing active mobility options. The project, which includes three pilot city use-cases—Athens, Valencia, and West Midlands-focuses on investigating the impact of the AGW on bicycle trips in the central area of Athens.

Prior literature has extensively explored sustainable urban transport policies and their impact on enhancing road safety and active mobility. However, a detailed analysis of the specific impact of interventions like AGW on bicycle trips in highly busy metropolitan areas was lacking. This study bridged this gap by utilizing interrupted time series analysis, to investigate the cycling before and after the implementation of exclusive lanes for cyclists and widened sidewalks on Panepistimiou st. Under AGW.

2 Methodology

2.1 The Athens Great Walk

Since Autumn of 2019, a series of novel traffic and parking interventions for the center of Athens were examined, part of the new mobility policy of the City of Athens and harmonized both with the Athens Sustainable Urban Mobility Plan. The new mobility interventions formed a major urban regeneration plan called the AGW.

In June 2020 a pilot implementation of a subset of the new mobility interventions was decided, following the example of several cities worldwide during the pandemic, to support active travel modes, assess the mobility interventions in practice, initiate a live public dialogue. On June 18, 2020, Panepistimiou St. Saw the expansion of its sidewalks and the establishment of a new cycleway, enhancing the width of the active infrastructure to 9 m. This transformation reduced the number of traffic lanes to three. However, on August 3, 2020, an extra traffic lane was allocated to motor vehicles, resulting in the road operating with four lanes. Figure 1 illustrates Panepistimiou St., generated using Tableau software.

2.2 Data Collection

To accomplish the paper's objective, the study utilizes crowdsourcing open data to analyze daily bike and e-bike trips recorded in the center of Athens before and after the implementation of AGW. The data were collected through the "Strava Metro" platform.

Strava is a crowdsourced fitness app [3], which utilizes anonymized, aggregated GPS data from its users to analyze activity over space and time (e.g. hour, year etc.) at fine spatial resolution three geometric units-street segments (edges), intersections, and polygons of trip origin and destination. They share this data via Strava Metro Service, offering a web-based platform to download activity information. This data is generated by users' mobile phones, which record their location using the built-in GPS device which are then matched to the nearest recreational or transport line from OpenStreetMap (OSM).

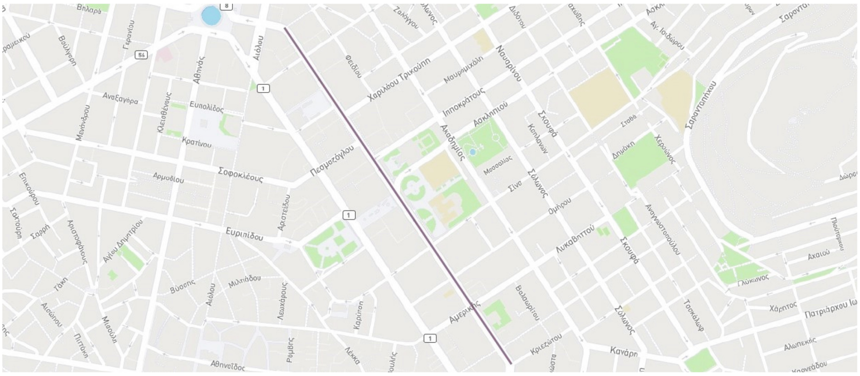

Fig. 1. The Panepistimiou St.

We restricted our analysis to the bikes and e-bikes trips recorded between June 2019 and June 2023 for 89 edges corresponding to 27 OSM street ids on Panepistimiou st., where the examined mobility intervention was implemented. To aggregate the trip data effectively, we elevated our analysis from the edge level to the street level, with Panepistimiou St. as our focal point. Throughout this process, we meticulously considered the minimum daily trip counts among the examined edges, considering that these trips encompassed the entire length of the street. The figure below presents the cycling trips on the street under consideration, including the examined interruptions.

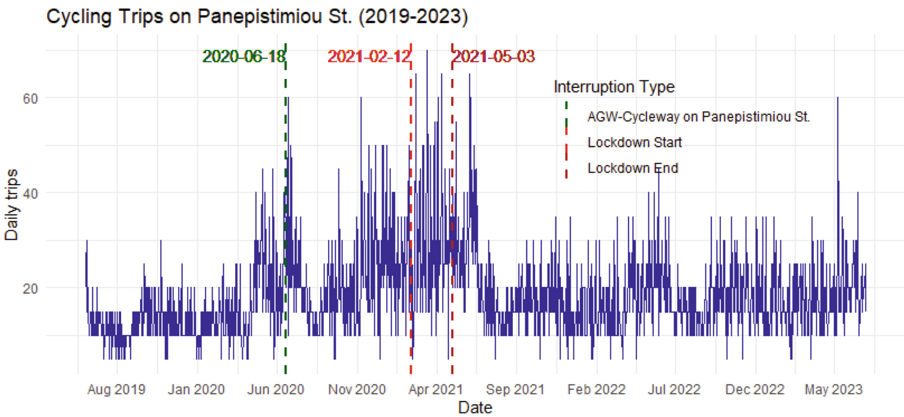

Fig. 2. Cycling trips on Panepistimiou st. and the examined interventions.

2.3 Interrupted Time Series

An interrupted time series (ITS) design involves regularly gathering observations at consistent time intervals from a group of entities both before and after an intervention. The data path may be disrupted by the intervention, leading to potential changes. An interrupted time series model assesses the difference between post-intervention predictions in a scenario where no intervention occurred, and post-intervention estimates when the intervention has been implemented.

In the current analysis, the primary intervention under examination is the implementation of the new cycleway and sidewalk expansion on Panepistimiou St. During AGW's pilot phase. Nevertheless, considering the data presented in Fig. 2, the end of the Covid-19 lockdown, which entailed the closure of educational institutions and retail establishments, should also be considered as an additional interruption.

For the examined interruptions, a linear regression model using generalised least squares was developed to estimate the effect of the intervention on the level change (change in level between time points immediately before and after the intervention accounting for the pre-intervention trend) and the change in trend (difference between pre-intervention and post-intervention slopes) for cycling counts. Autocorrelation between residuals was assessed using an autoregressive moving average (ARMA) model with the nlme package in R.

3 Results and Discussion

To provide a comprehensive overview, a detailed snapshot of daily cycling trips on Panepistimiou St. Across multiple years, with colors used to facilitate comparisons of trip numbers for the same months across different years, is provided via the following table. In 2019, cycling activity remained relatively modest. However, in 2020, the landscape altered significantly, primarily due to the introduction of the new cycleway in June. The positive impact persisted into 2021, potentially influenced by concurrent lockdowns, promoting active mobility. Although 2022 and 2023 recorded a slight decline in cycling traffic, levels remained notably higher than those observed prior to the AGW intervention in 2019 (Table 1).

Table 1. Monthly summaries of daily cycling activity on Panepistimiou St.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2019	n/a	n/a	n/a	n/a	n/a	15	11	9	15	14	13	13
2020	13	14	13	19	24	**26**	21	13	19	18	24	27
2021	26	28	29	31	27	30	16	14	18	18	18	14
2022	16	15	14	20	22	20	15	14	18	20	19	18
2023	18	17	18	17	21	21	n/a	n/a	n/a	n/a	n/a	n/a

In the following model, "Time" variable represents the study days, tracking the progression of time from 0 to 1477 day. "AGW_new_Cycleway" and "Covid19_Lockdown_end" are binary variables indicating whether the specific intervention occurred at a given time. "AGW_new_Cycleway_time_since" and

"Covid19_Lockdown_end_time_since" are variables measuring the time that has elapsed since the intervention took place, providing insight into the post-intervention period. It must be noted that the correlation structure of the following model is specified as an ARMA(0,1) process (Table 2).

Table 2. Uncontrolled ITS analysis

	Value	t-value	p-value	
(Intercept)	9.789	9.318	0.000	**
Time	0.026	5.359	0.000	**
AGW_new_Cycleway	−2.180	−1.408	0.159	
AGW_new_Cycleway_time_since	0.015	1.975	0.049	**
Covid19_Lockdown_end	−11.190	−8.274	0.000	**
Covid19_end_time_since	−0.043	−6.779	0.000	**

The positive coefficient for "Time" suggests a slight upward trend in daily cycling trips over time. For each 100 days, we can expect additional 3 cycling trips. Notably, the introduction of the new cycleway and sidewalk expansion had a marginally adverse but not statistically significant effect on daily cycling trips, potentially attributed to ongoing construction during the first days. However, the time elapsed since this intervention showed a positive effect, contributing to increased cycling trips.

The large negative coefficient of "Covid19_Lockdown_end" indicates a substantial decrease in daily cycling trips associated with the end of the Covid-19 lockdown, implying that the lockdown had a significant negative impact on cycling activity. Additionally, the time elapsed since the lockdown demonstrated a further small but statistically significant reduction in cycling trips.

4 Conclusion

This paper endeavors to explore the impact of the newly implemented cycling infrastructure along Panepistimiou St. Within the AGW framework. To this end, an ucontrolled ITS analysis is conducted harnessing crowdsourced open data on bike and e-bike trips collected through the "Strava Metro" platform.

The analysis results highlight the dynamic nature of urban cycling patterns and the intricate relationship between infrastructure enhancements, external disruptions, and time trends. While interruptions such as the Covid-19 pandemic can lead to temporary extreme changes in cycling, well-executed active mobility infrastructure projects, like the AGW, can ultimately promote and sustain cycling as a viable mode of urban transport contributing to the increase of the overall volume of cycling trips over time.

It's imperative to acknowledge that, akin to other forms of crowdsourced data, Strava constitutes a relatively small sub-sample of the overall population. As a result, the data may require calibration against fixed-point counter stations to facilitate population-level estimations of total activity volume [4, 5]. Addressing this limitation could further enhance the robustness and representativeness of the findings of the current analysis.

Understanding these dynamics is crucial for urban planners and policymakers as they work to create cyclist-friendly environments offering valuable lessons for transforming densely populated urban spaces into safer, greener, and more efficient environments. Overall, this research contributes to the growing body of knowledge on sustainable urban transportation, fills a novel gap on how highly busy, metropolitan areas can be transformed and offers practical particular insights into promoting cycling as a viable mode of transport in Athens.

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Towards Low Carbon and Sustainable Mobility: Reassessing Roundabouts Design

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Abstract. The EU sets the path towards zero CO_2 emissions for new passenger cars in the future. Reaching net zero, there will be a period of co-existence between conventional vehicles and zero-emission vehicles. Engineers and policy-makers should proceed to direct approaches, taking steps to reduce road pollution by reassessing the road design. Roundabouts enforce speed variations. Depending on the driving behaviour, can result in high pollutant emissions. The objective of this paper is to understand the factors and the parameters that contribute to high pollutant emissions. The trajectories of 260 vehicles at six multilane roundabouts were analyzed. Video image processing techniques allowed the extraction of accurate kinematic characteristics gathered on the field using a UAV. The VSP methodology was applied to calculate carbon dioxide. The results of the quantitative analysis demonstrate strong relationships with road geometry. Road designers should consider the aspect of the environment and choose geometric variables wisely.

Keywords: Pollutant Emissions · VSP · Road Design · Trajectory · GHG

1 Introduction

European Commission recently adopted a strategy to reduce greenhouse gas emissions. Since road transport is responsible for 76,7% of total European transport emissions [1], the EU sets the path towards zero CO_2 emissions for new passenger cars in the future [2]. Reaching net zero would require a total displacement of conventional vehicles from zero-emission vehicles. To achieve this, there will be a period of co-existence between conventional vehicles and zero-emission vehicles.

Therefore, engineers and policymakers should proceed to direct approaches, taking steps to reduce road pollution by reassessment of the road design. Bearing in mind that vehicular emissions have increased considerably over the last few years, the current transport system might not be sustainable and needs to be adjusted.

Environmental and transportation researchers followed different approaches during the last years to examine and provide efficient solutions. Promoting a shift to low-emission mobility remains the main objective. However, the increase in traffic congestion

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reinforces the need for the integration of different modes of transport, including the adoption of innovative technologies and methods for traffic management.

Roundabouts are among the most effective intersections as they significantly contribute to better road safety and increase road capacity. Except for improving traffic flow conditions, they can contribute to less vehicular emissions and fuel consumption by reducing delays and queues. However, their design forces vehicles to increase and decrease their speeds many times during their manoeuvring, especially during free flow conditions. According to these, depending on the driving behaviour, roundabouts can result in high accelerations and therefore high pollutant emissions.

The main purpose of this experimental research is to understand the factors of driving behaviour and the parameters of roundabout geometry that contribute to high pollutant emissions.

2 Literature Review

The factors that contribute to fuel consumption variations and road transport emissions are distinguished by the following five main categories [3]; driving behaviour, vehicle fleet and vehicular characteristics, traffic conditions, road geometry, and environmental conditions.

Driving behaviour, traffic conditions and road geometry contribute significantly to vehicle manoeuvres and speed variations of vehicular kinematic characteristics and therefore to pollutant emissions. However, the vehicle fleet and the vehicular characteristics, together with environmental conditions (e.g., temperature, humidity and atmospheric pressure) contribute directly to fuel consumption and emissions.

Many researchers are dealing with these issues by analyzing vehicle trajectories and speed profiles [4–8]. Vehicle trajectories can provide information concerning the kinematic characteristics of the vehicles (e.g., speed, acceleration and deceleration), driver behaviour (e.g., gap-acceptance), as well as traffic conditions (e.g., traffic congestion). Various methodologies and simulation tools have been applied to compare pollutant emissions between roundabouts and signal-controlled intersections [9]. The results indicate that in the absence of traffic congestion roundabouts can contribute to higher rates of pollutant emissions. Driving behaviour is a major factor in that.

Additionally, American researchers [10] concluded that the environmental benefits resulting from the conversion of a signalized intersection into a multilane roundabout depend mostly on the distribution of traffic. Upon this, driving behaviour variations can contribute decisively to the total amount of pollutant emissions [11, 12]. It is obvious that even if roundabouts are generally characterized by consistent speeds, fewer queue lengths, delays and stops, free-flow conditions can contribute to high emissions of air pollutants because of driving behaviour and significant speed variations.

3 Methodology

3.1 Site Selection and Sampling

The selection process adopted to identify the examined roundabouts for the analysis was based on the following main criteria; a) Modern multilane roundabouts ensured the variability of driving behaviour (e.g., large variations for vehicular speeds and trajectories),

b) free-flow speed traffic conditions were necessary to study and assess the impact of driving behaviour on vehicle emissions along roundabouts during uncongested periods, c) weather conditions and ensured the ability to conduct UAV surveys, and finally d) roundabouts of various geometric elements were selected to understand the trade-offs of capacity, safety and environmental footprint during roundabout design.

Finally, on-field data were collected for eight (8) through movements of six (6) multilane roundabouts located in 3 municipalities of Greece. A power analysis was performed to estimate and ensure the minimum amount of required data for the analysis. Assuming an 80% power, a significance level of 5% and a medium effect size, the minimum sample size for the quantitative analysis was estimated to be around 85 [13, 14]. Based on that, the total number of 260 trajectories that were included in the final sample is sufficient for the correlation analysis.

3.2 Field Data Collection

Two types of equipment were used to monitor traffic conditions and extract accurate vehicle trajectories: a) a quadcopter UAV and b) an RTK GNSS receiver. The collection and analysis of high-resolution data such as vehicle trajectories are challenging concerning the analysis of driving behaviour [15]. Two types of data were collected in this experiment; (a) data relies on the geometric elements of the roundabout and (b) data regarding the kinematic characteristics of the vehicles. The geometric features of the roundabouts were measured on CAD software by digitizing georeferenced frames, following the methodology that is extensively described in [7].

The software QGIS [16] was used for the extraction of the kinematic characteristics of vehicles. The selected geographic reference was the "GGRS87/Greek Grid". Trajectories of vehicles were built based on the identification of the actual vehicle locations per second. Specifically, the centre of the front bumper of each vehicle was identified in the co-registered images and the coordinates were extracted. Vehicle velocities and acceleration rates were calculated at the entrance, in the middle and at the exit of the roundabout following a more detailed procedure of image co-registration per 0.2 s. The accuracy of vehicle speeds regarding this method was calculated to be less than 2.3 km/h as the georeferencing procedure provided low values of RMSEs.

3.3 Vehicle Emissions Calculations

To calculate vehicle emission, the Vehicle Specific Power (VSP) model was used [17]. A simplified and applicable form of the VSP model is presented in Eq. 1. The VSP was initially calculated based on the vehicular kinematic characteristics and the road geometry, and then apportioned to the corresponding categories that represent different driving behaviour conditions [18]. Each VSP category is assigned a specific amount of pollutant emissions, considering the appropriate values for both petrol and diesel light vehicles [10, 19]. The estimated share between them was calculated to be 90.1% and 8.6% respectively [20]. The rest of the total amount was excluded from the analysis, assuming a small share for zero-emission vehicles.

$$VSP = v * \left[1{,}1 * a + 9.81 * (sin(arctan(grade))) + 0{,}132\right] + 0.00302 * v^3 \quad (1)$$

where v is the speed (m/s), a is the acceleration (m/s2) and grade is the road grade (%).

Pollutant emissions were calculated per 0.5 m. It is highlighted that the spatial distribution of pollutant emissions can contribute to a better understanding of potential road design adjustments concerning environmental aspects.

4 Vehicle Emissions Analysis and Results

The final database consists of 260 cases (pollutant emissions of vehicle trajectories). The hypothesized explanatory variables considered for the analysis were based on previous analyses and causal mechanisms suggested by the existing literature. The statistical software IBM SPSS Statistics [21] was used to perform the analysis.

According to the results of the distribution of the VSP categories, it is concluded that categories 4 to 6, which indicate an increase in vehicular speed and accelerated manoeuvres, gather the highest rates. High percentages are observed for categories 1 to 3, indicating vehicular deceleration and constant speeds. The impact of roundabout geometry on driving behaviour significantly contributes to the increase of pollutant emissions as vehicle accelerations and decelerations are observed during their manoeuvres.

Moreover, each of the examined cases results in large spreads of carbon dioxide values. The observed high variability of pollutant emissions (minimum values of 72.9 g/km and maximum value of 454.1 g/km) is strongly related to both aggressive and defensive driving behaviours of roundabout vehicle users.

The normality of data distribution for each quantitative variable was examined by the Kolmogorov-Smirnov (K-S) test [22]. Results ($p < 0.05$) indicated the violation of the assumption of normal distribution for all examined variables. Therefore, Spearman's Rho correlation was applied to investigate the correlation between the dependent variable (CO_2 emissions) and the independent variables as presented in Table 1.

Table 1. Spearman's Rho Correlation Results.

Variable	Spearman's rho	Significance (2-tailed)
ICD - Inscribed circle diameter (m)	-0.190^{**}	0.002
CID - Central island diameter (m)	-0.354^{**}	<0.001
CW - Circulating width (m)	0.260^{**}	<0.001
TAW - Truck apron width (m)	-0.242^{**}	<0.001
EW - Entry width (m)	0.312^{**}	<0.001
EA - Entry angle (°)	-0.208^{**}	<0.001
EXW - Exit width (m)	-0.225^{**}	<0.001
EXR - Exit radius (m)	-0.446^{**}	<0.001

The highest significant positive correlations are identified between carbon dioxide and the exit radius ($r = -0.446$, $p < 0.001$), as well as the central island diameter ($r = -0.354$, $p < 0.001$). Based on that, the increase of the values of these two geometric elements can contribute to less pollutant emissions because of constant speeds and defensive driving behaviour. On the other hand, it is observed that as the entry width gets higher, the amount of carbon dioxide increases ($r = 0.312$, $p < 0.001$).

According to the correlation analysis results, it is highlighted that the amount of pollutant emissions is associated with the geometry of the roundabout. This is reasonable considering the great impact of road geometry on speed variations.

5 Discussion

Roundabouts are among the most effective intersections as they significantly contribute to better road safety and increase road capacity. Except for improving traffic flow conditions, they can contribute to less vehicular emissions and fuel consumption by reducing delays and queues. However, their design enforces to significant speed variations and therefore high pollutant emissions.

The results of the quantitative analysis performed on 260 vehicle trajectories concerning 6 roundabouts located in Greece by applying the VSP model, demonstrate strong relationships between the carbon dioxide and the geometric features of roundabouts. The proposed method for the spatial distribution of pollutant emissions can contribute to a better understanding of potential road design adjustments.

The trade-offs of safety, capacity, and environment must be recognized and assessed throughout the design process. Road designers should have on their mind the aspect of the environment as well and choose geometric variables wisely. Further research should be conducted for saturated conditions to adopt a holistic approach to better understand the contribution of road geometry on pollutant emissions.

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Sustainable Transport Roadmap to Support Sustainable Economy in the Slovak Republic

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Abstract. This study underscores the increasing global commitment to address climate change and allocate emissions accurately to economic sectors. Slovakia's innovative Air Emission Accounts methodology is pivotal in understanding emissions sources and customizing policies effectively. The transport sector, contributing significantly to GHG emissions, warrants special attention for decarbonization. Emission allocation relies on vehicle category, mileage, goods transported, and owner, providing comprehensive fleet data for each economic category. National GHG projections and proposed measures, including intermodal transport promotion, play a crucial role in achieving sustainability. Identifying sectors with the highest carbon footprint, such as transportation, real estate, and retail, highlights the need for emission reductions. Monitoring the carbon footprint, gross value added, and employment reveals a promising strategy for tailored interventions, fostering sustainability across regional, local, and national levels.

Keywords: air emission accounts · projections · carbon footprint · PaMs

1 Introduction

In recent years, the global community has witnessed an escalating commitment to combat climate change and reduce GHG emissions. To turn these commitments into tangible results, it is utmost important to accurately allocate emissions across economic activities. Slovakia has emerged as a noteworthy example, having adopted a comprehensive methodology for Air Emission Accounts (AEA) [1]. This approach represents a crucial step forward, enabling a deeper understanding of the primary culprits in emissions production and facilitating the tailoring of PaMs (policies and measures) to target specific sectors more effectively.

One sector that permeates all economic activities and exerts significant influence over emissions is the transport sector. In 2021, it contributed a substantial 25% to the total greenhouse gas (GHG) emissions within the European Union (EU) [2] and 18% in Slovakia [2]. This sector's emissions have followed an upward trajectory since the 1990s, rendering it a pivotal arena for decarbonization and sustainable transformation.

The adoption of Slovakia's novel methodology for emissions and energy consumption allocation has ushered in profound changes in the understanding of emissions

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dynamics. It has unearthed previously underestimated sources of emissions, exemplified by the retail sector's reliance on vans (N1 category vehicles) leading to higher emissions. Conversely, companies engaged in the transportation of goods and people have demonstrated lower emissions. This revelation serves as a clarion call for reevaluating sector-specific strategies and policies and measures (PaMs), identifying gaps and barriers within existing policies, and redirecting pressure toward sectors where sustainability is both environmentally and economically viable.

2 Methods

2.1 Emission Allocation

The emission allocation methodology relies on four main parameters: vehicle category, annual mileage, transported goods quantity and vehicle owner (private or company). The methodology employs a detailed analysis, utilizing data from various sources and integrating COPERT [3] emission model outputs. The resulting allocation matrix provides a comprehensive breakdown of the vehicle fleet for a specific year, offering detailed information for each NACE rev.2 category.

2.2 National GHG Projections and PaMs

Emission projections are primarily being developed at the national level, encompassing the entire country. Key national projections in this context have been prepared and presented by experts Horváth and Szemesová [4]. These projections, coupled with proposed PaMs, serve as a robust basis for more precise targeting and quantification of greenhouse gas (GHG) emission savings across various economic sectors. Among the most significant measures are initiatives aimed at electrifying transportation and promoting intermodal transport, both of which play a pivotal role in transitioning toward a more sustainable and low-carbon economy. These projections and policies are an integral part of broader efforts to reduce GHG emissions and achieve environmentally acceptable and economically sustainable goals at the national, local or sectoral level.

2.3 Calculation of Carbon Footprint

The carbon footprint was calculated as an average value for the period from 2013 to 2021, aiming to smooth out potential year-to-year economic fluctuations. This value was determined as the production of fossil CO_2 per 1 million Euro of gross value added (GVA) and computed separately for each main NACE rev.2 category (A-U) based on data available in the Statistical Office of the Slovak Republic's databases and the emissions allocation methodology outlined in Sect. 2.1. These data serve the purpose of estimating the amount of emissions produced for generating 1 million Euro within a specific economic activity. Furthermore, this value facilitates the identification of the most pollutant sectors.

A similar approach was employed in determining the production of fossil CO_2 per employee, allowing for an assessment of potential socio-economic impacts. It is important to note that this section primarily serves an illustrative function and should be incorporated into further studies that primarily focus on the social impacts of emissions reduction in economic activities.

3 Results

In Slovakia, in the year 2021, there were more than 2,970,000 registered vehicles [2]. The detailed breakdown of these vehicles is presented in Table 1. Out of the total number of passenger vehicles, in average only 18% are utilized for economic activities. Conversely, a substantial 84% of heavy-duty vehicles are employed within specific economic activities classified under NACE rev.2. The sector responsible for the highest emissions production – transportation activities (Category H, covering road and pipeline transportation, water and air transportation, warehousing, support activities for transportation, postal, and courier activities) – comprises just 10% of all economically used vehicles. However, it contributes in average to as much as 45% of all emissions from economic activities (Fig. 1).

Table 1. Breakdown of registered vehicles.

Vehicle category	Total number	NACE rev.2 registration	Physical entity registration
Passenger cars	2 460 567	452 193	2 008 374
Light commercial vehicles	267 080	125 505	141 575
Heavy-duty vehicles	77 551	64 876	12 675
Buses	7 871	7 280	591
L-category vehicles	157 092	17 487	139 605

Based on emissions calculations and obtained data on GVA, and thus CO_2 per million Euro, the sectors with the highest carbon footprint were identified. These sectors include Category H (Transportation and storage), which produce an average of 537 tCO2/mil.€, category L (Real estate activities) producing 210 tCO2/mil.€, category G (Wholesale and retail trade; repair of motor vehicles and motorcycles) generating 203 tCO2/mil.€, and category F (Construction) with 92 tCO2/mil.€ (see Fig. 2). Each of these categories surpasses the emissions per million euros as compared to the national average, which stands at 68 tCO2/mil.€.

When it comes to CO2 emissions per employee, these categories exhibit variations. The highest CO2 production per employee is observed in Category F, with 13 tCO2/employee in the sector. It is followed by Categories G, with 13 tCO2/employee in the sector, J (Information and communication) producing 13 tCO2/employee in the sector, E (Water supply; sewage, waste management, and remediation activities) generating 3 tCO2/employee in the sector, and L, producing 2 tCO2/employee in the sector. The national average is 1.75 tCO2/employee in the sector (see Fig. 3).

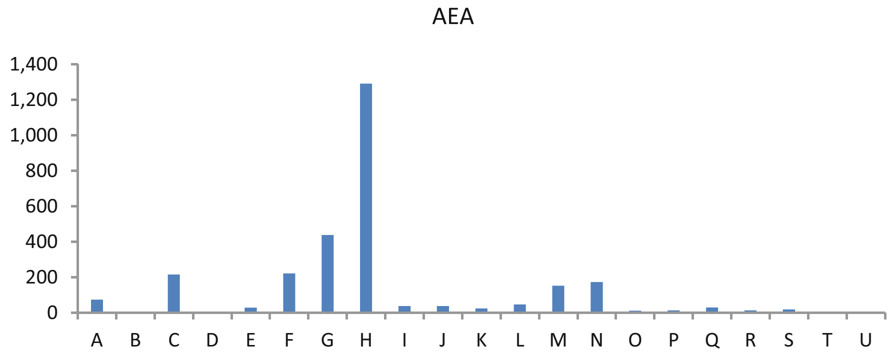

Fig. 1. Breakdown of road transport CO2 emissions into basic NACE rev.2 categories in kilotons (kt) (average of 2013–2021).

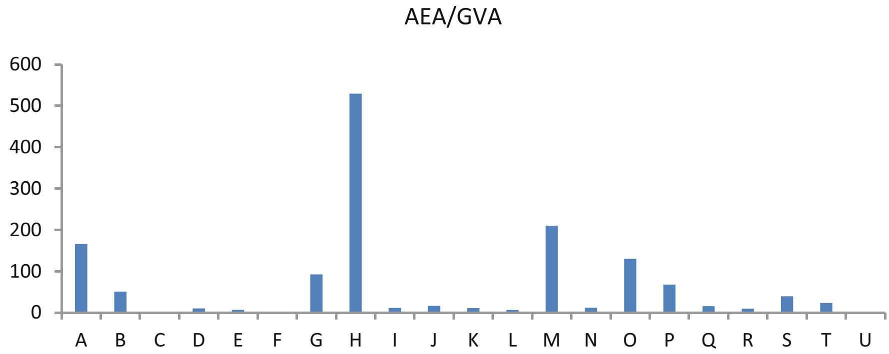

Fig. 2. CO2 emission production per 1 million EURO (tCO2/mil.€).

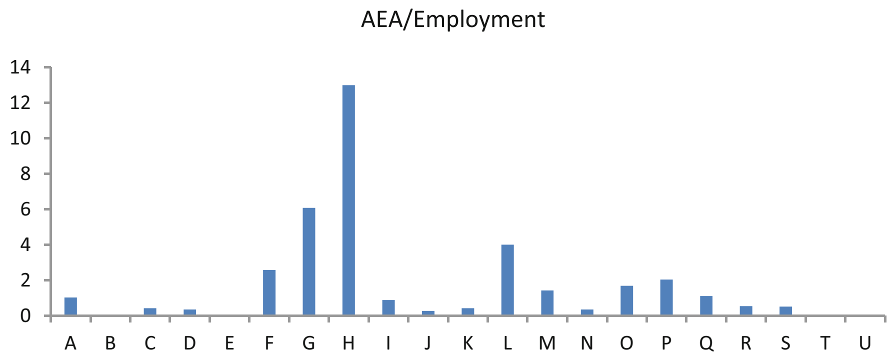

Fig. 3. CO2 emission production per employee in sector (tCO2/emp).

These data have shown us that the most substantial emission reductions are required in Categories H, F, and G. Category H stands out significantly in terms of absolute values, and according to calculations, it will necessitate a reduction of approximately 1,110 kt CO2. Based on the study by Horváth and Szemesová [4], achieving this reduction is feasible through robust support for intermodal transportation and, consequently, an overall modal shift in the freight sector. According to this study and Slovakia's commitment within the White Paper on Transportation, the country should reduce freight transport by 30% by 2030 and 50% by 2050. In the case of the other two categories, emissions need to be reduced by approximately 350 kt CO2 in total. Since a significant portion (22% in Category G and 12%) of emissions originates from personal vehicles used in this sector, it is appropriate to direct some low-carbon personal vehicle measures to this category.

The full potential of monitoring the carbon footprint in conjunction with gross value added and employment undoubtedly necessitates a more comprehensive analysis. Nonetheless, these outcomes indicate that this approach may offer a promising avenue for a more precise implementation of policies and measures within the realm of transportation, particularly at a sub-national level. By scrutinizing the interplay between carbon emissions, economic output, and employment, a deeper understanding of emissions' socioeconomic impact can be obtained. Such insights can inform the targeted design of interventions, not only on a national scale but also at sectoral level, enabling more effective mitigation strategies tailored to specific contexts and requirements.

4 Conclusion

The carbon footprint analysis for the period 2013–2021 has identified significant emissions in specific sectors. Notably, Category H, which includes road and pipeline transportation, water and air transportation, and related activities, contributes the highest emissions. Achieving the required reductions in these sectors may involve promoting intermodal transportation.

The study highlights the importance of targeting emission reductions in categories H, F, and G. While Category H requires the most substantial reduction, other sectors need emissions reduction efforts as well, particularly those involving personal vehicles. The potential for monitoring the carbon footprint, combined with gross value added and employment data, promises a more precise approach to transportation policy implementation at various levels, ensuring that interventions are tailored to specific contexts and requirements. This approach offers a promising path towards effective mitigation of GHG emissions and a sustainable future and can possibly redirect the financial support to economic sectors that need it.

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CargoTube Network Analysis Based on an Agent-Based Modelling: Lower Saxony Case Study

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Abstract. This research considers the case of a CargoTube physical Intranet network in Lower Saxony, connecting multiple automotive production sites. Through the economic growth of the region and its companies including the Volkswagen plant in Wolfsburg increased freight, especially on trucks, is brought to the region which brings along a lot of traffic, noise and pollution. For green transportation of goods, we need zero-emissions vehicles and new transport systems like CargoTube. The CargoTube transport solution not only brings in new Hyperloop technology such as the introduction of a low-pressure tube environment and a linear motor but combines these innovations with established technologies such as the wheel-rail interface. A system based on CargoTube transport solution autonomously loads and unloads standardized containers. Transporting containerized cargo hundreds of kilometers in minutes enables the just-in-time supply chains needed for an economy and increases company profits. The research is devoted CargoTube transport network analysis with the help of the multi-agent simulation system TraPodSim created based on AnyLogic software. The questions to be answered by the simulation are related to analyse the CargoTube Transport Network for a certain set of KPI's and analysis of effectiveness of integration with other transport mode.

Keywords: Transportation · CargoTube · Simulation · Indicators · Effectiveness

1 Introduction

Today, the transportation industry is the fastest-growing source of global carbon emissions, and achieving sustainability principles in such areas requires multi-disciplinary research and innovation. For green transportation of goods, we need zero-emissions

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vehicles and new transport systems like CargoTube. Innovative cargo vehicles should offer services at lower prices, with less environmental impact, improved safety, and with a higher degree of reliability of operations. However, costs will arise for logistics companies when introducing innovative vehicles (the purchase of new vehicles, software, and other costs) that may arise before their scaling and wide coverage by users, etc. Regarding emissions, most of these new vehicles are 100% powered by electricity, and thus emissions are not produced directly by the EU requirements and can be avoided with a fully renewable electric grid. All these changes can become a catalyst for more fundamental changes in transport systems, as well as in the overall design of transport infrastructure.

The CargoTube transport solution realistically enables a high-speed transportation system to come to market quickly with reasonably low levels of investment in infrastructure providing much greater flexibility for the TEN-T network. A system based on the CargoTube transport solution autonomously loads and unloads standardized containers to reduce congestion and increase operational efficiency. Transporting containerized cargo hundreds of kilometers in minutes enables the just-in-time supply chains needed for the economy and increases company profits.

We provide CargoTube transport network analysis with the help of the simulation system TraPodSim, created based on AnyLogic simulation software [1]. This system, TraPodSim, is designed to create a multi-agent simulation model for the process of transporting goods by vehicles along the routes of the transport network specified for a particular region. The questions to be answered by the simulation are related to analyzing the CargoTube Transport Network for some set of KPIs and analysis of the effectiveness of integration with another transport mode.

2 CargoTube Concept

Hyperloop is a transport system in which cargo is transported inside a tube with virtually no air resistance, since ambient air pressure is reduced down to a given low pressure, approx. 0.1% to 1% normal pressure at sea level [2]. Cargo is transported using vehicles, which are commonly referred to as pods. The highest transport speeds can be achieved using linear induction motors and magnetic levitation. Terminals of the Hyperloop system are airlock chambers in which loading/unloading operations are performed to transfer cargo to atmospheric pressure.

The CargoTube system is based on the Hyperloop concept, but its feature is the usage of a rail track that is laid inside the tube, resulting in reduced infrastructure costs for transportation. It also becomes possible to abandon the production of special steel tubes of larger diameters and use tubes that are already used in the infrastructure of gas pipelines or water pipes. These factors led to a significant reduction in costs both-during the creation of the CargoTube system and during its operation [3]. The CargoTube system will allow you to reach a transportation speed of up to 300 km/h, but even at a speed of 150 km/h, such a system can be very effective both in terms of productivity and in terms of environmental impact [4].

3 Case Description

This research considers the case of a CargoTube Physical Intranet Network in Lower Saxony, connecting multiple automotive production sites. Volkswagen, for example, identified the production sites in Wolfsburg, Braunschweig, and Salzgitter as key to their electric mobility strategy as they are forming their "Battery Valley". Many additional locations within northern Europe could be connected, including suppliers.

It is known that Volkswagen Group has begun construction of its factory for the production of batteries for electric vehicles in the city of Salzgitter [5]. One of the consumers of these batteries will be a factory in Wolfsburg, where starting from 2025, the number of electric vehicles produced will be increased to 500,000 per year. That means that every year 500,000 batteries weighing from 800 to 1000 kg must be transported from Salzgitter to Wolfsburg (with 320 working days on average, 1563 batteries must be transported per day). With a known load capacity of the vehicles that will be used to transport batteries, it is easy to estimate the number of trips per day, and the associated fuel costs and greenhouse gas emissions.

As an alternative for the transportation of batteries, it is proposed to use the CargoTube system, which in the form of a circular route will connect the plants in Salzgitter and Wolfsburg (Fig. 1). Batteries will be transported from Salzgitter to Wolfsburg, and empty containers will be transported in the opposite direction, that is, special equipment used when placing batteries on the pod. A constant number of pods will circulate in the system. In the route variant shown in Fig. 1, the distance between the terminals of the network, which are loading/unloading stations, is approximately 45 km. It is assumed that the maximum speed of pods will be 150 km/h.

Fig. 1. Sketch of the movement of 24 pods along a circular route (size of pods is not in scale) (image produced using OpenStreetMap, an open online map service).

4 Conceptual Model

Two types of processes need to be modeled: a) the process of moving the pod fleet along the ring route and b) the processes of processing pods at two stations located at production plants in the cities of Salzgitter and Wolfsburg. The purpose of the simulation is to check the technical feasibility of options for creating a CargoTube system, calculate the required number of pods, as well as estimate the amount of energy consumed and CO_2

emissions projected. Within this work, two variants have been investigated that differ in pod capacity: a) one pod carries 2 batteries and b) one pod carries 4 batteries. Part of the conceptual model is analytical calculations, which are used to determine the values of the input parameters of the model. These values must be mathematically consistent with each other since there are certain spatial and temporal dependencies between them. Without such coordination, the model will not be able to correctly display the process of simultaneous synchronized movement of several dozen pods.

A special group of input parameters is formed by energy consumption indicators in various modes of pod movement. Since there is currently no data for measuring such indicators in a real system, the analogy between the pod movement in CargoTube and the movement of a conventional tram was taken into account [6]. All input parameters of the model are shown in Table 1. Table shows the power values for one pod at the beginning of acceleration P_max, when driving at maximum speed P_norm and the beginning of braking in regenerative mode P_reg. A feature of the pod's movement along the route is the speed change shown in Fig. 2 for one direction of travel.

Table 1. Input parameters of the simulation model.

Name of data	Variable notation	Value	
Specified parameters			
number of cargo units per day (units)	X1	1562.50	
number of working hours per day (hours)	X2	16	
distance between stations (km)	X3	45.126	
number of cargo units in the pod (units)	X4	**2**	**4**
maximum pod speed (km/h)	X5	150	150
acceleration time to maximum speed (min)	X6	0.71	0.71
deceleration time to zero speed (min)	X7	0.71	0.71
power on beginning of acceleration (kW)	X8	60	80
power when driving at maximum speed (kW)	X9	20	28
power at the beginning of braking (kW)	X10	-60	-80
Calculated parameters			
number of cycles per day (number)	Y1	781.25	390.63
maximum handling time (min)	Y2	1.23	2.46
minimum number of pods (number)	Y3	32.53	17.27
specified number of pods (number)	X11	33	18
waiting time in front of station (min)	Y4	0.29	0.90
distance between pods (km)	Y5	2.73	5.01

Diagram on Fig. 2 can also be shown for movement in the opposite direction, but at the same time, some input parameters, except v_{max}, t_{cycle} and $\tau_{handling}$ may be different

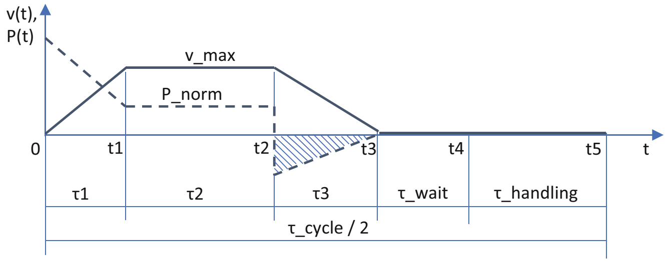

Fig. 2. Diagram of the changes in pod speed and power for one direction of movement.

since the direction of Wolfsburg pod carries a payload, and in the direction of Salzgitter – an empty container. It also shows the change in power consumed by pod motors. The amount of energy consumed is numerically equal to the area under the graph P(t). In Fig. 2 the area corresponding to the energy returned to the grid when braking the pod in regenerative mode is shaded.

It is necessary to specify the number of hours in the working day, as well as the time intervals τ1 and τ3, shown in Fig. 2. Based on these data, additional input parameters of the model are calculated. To calculate these parameters, simple formulas are used, the most complex of which is the formula for calculating of minimum number of pods:

$$Y3 = 2 * (1 + X6/2/Y2 + X7/2/Y2 + X3/X5/Y2 * 60) \quad (1)$$

The user must specify a specified number of pods, which must not be less than the parameter Y3.

5 Development and Application of a Multi-agent Model

To simulate the movement of pods along a circular route, a multi-agent paradigm was applied in the AnyLogic software environment. Figure 3 shows a state chart that defines the behavior of each agent of the "pod" type. The depo1 and depo2 blocks are used only when initializing the model, that is when directing pods to a route at precisely defined points in time.

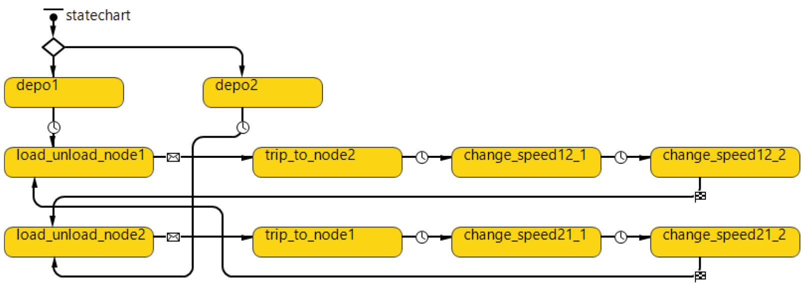

Fig. 3. Statechart, which defines the behavior of an agent of the pod type.

The discrete event paradigm has been applied to simulate pod processing instances at two stations located at both ends of the route. To do this, an agent of the pod type goes to process flow with the name Node1 or Node2.

The main limitation that applies to any variant of the model is the parameter Y2 (maximum handling time), since its value is uniquely determined by the number of goods transported during the working day. As the number of pods used increases, the waiting time in front of the station increases, but the distance between pods decreases.

Results related to the energy consumption for the movement of pods and for pumping air out of the space of the processing station before the start of the pod are shown in Table 2. If the methods of generating electricity consumed by CargoTube are known, then it will be possible to calculate the corresponding volumes of CO2 emissions.

Table 2. Main simulation results.

Name of indicator	Value	
number of cargo units in the pod (units)	**2**	**4**
energy consumed per cycle, taking into account recuperation and evacuation of air at the station (kWh)	14.23	19.45
energy expended by all pods per day (kWh)	11120.00	7596.50

6 Conclusions

The developed model is designed to conduct simulation experiments in which the user can adapt any specified parameters shown in Table 1. By simply copying model elements to AnyLogic and adding new tables similar to Table 1, this model can be used to study the CargoTube transport network scaled to an arbitrarily complex structure.

The innovative transport system CargoTube is most likely capable of a much higher capacity with increased automation and frequency without overload on the existing networks and while reaching for climate neutrality for Europe, it can drastically reduce operating energy demand and emissions in the future.

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Sustainable and Greenhouse-Gas-Neutral Initiatives Within European Ports: Insights from the MAGPIE Project

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Abstract. This paper investigates the significance of ports in the energy transition (ET) and decarbonisation. Ports, being vital in energy value chains, play a critical role in curbing energy use and emissions. The paper draws from the MAGPIE project, funded by the Horizon 2020 programme, which showcases energy and digital solutions in a real-world setting. The paper focuses on sustainable initiatives in 12 European sea- and inland- ports, analysed through interviews and secondary data. Findings reveal that while many ports discuss ET, few have transformed their plans into significant actions due to technological, regulatory, and financial challenges. Three core themes emerge from the review: ET infrastructure, seagoing ships and hinterland transport, and governance. Ports need more actionable strategies for ET, with port authorities spearheading the adoption of sustainable technologies through collaboration.

Keywords: Energy transition · ports · MAGPIE Project · alternative fuels · green ports · decarbonisation

List of Abbreviations

CCS	Carbon Capture and Storage
CCU	Carbon Capture and Use
EC	European Commission
ESPO	European Seaport Organisation
ET	Energy Transition
ETIT	Energy Transition Infrastructure and Technologies
GHG	Green-House Gas
IMO	International Maritime Organization
LNG	Liquified Natural Gas
MAGPIE	sMArt Green Ports as Integrated Efficient multimodal hubs
OPS	Onshore Power Supply

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P2X	Power to X
RED	Renewable Energy Directive
SHT	Seagoing Ships and Hinterland Transport Fuels
WtE	Waste to Energy
WtF	Waste to Fuel

1 Introduction

In Europe, ports are central to the low-carbon transition, especially with transport accounting for 25% of the EU's Green-House Gas (GHG) emissions. The "Fit for 55" package, introduced in 2021 by the European Commission (EC), aims to reduce GHG emissions by 55% from 1990 levels by 2030 and includes measures such as setting a GHG cap for ships entering EU ports and extending the EU Emission Trading Scheme to maritime transport. The Renewable Energy Directive (RED) seeks to increase the EU's renewable energy target to 40% by 2030, with an emphasis on the transport sector. Decarbonisation initiatives at the European level converge in their objectives with the recent efforts of the International Maritime Organization (IMO), which revised its decarbonisation strategy in July 2023 to reach carbon neutrality for international shipping around 2050.

The EC and industry bodies, such as the European Seaport Organisation (ESPO), have highlighted ports' potential in promoting cleaner technologies and low-carbon energy sources. Ports, due to their strategic position in transport chains and proximity to industrial hubs, can influence global emission reductions [1]. They support logistics at sea and on land, and energy management within ports can contribute to lowering emissions [2]. Inland ports, as intermodal hubs, have also potential in advancing low and zero-emission transport corridors [3]. The regulatory shifts and technological developments present both challenges and opportunities for ports in the energy transition (ET). As technologies evolve and new solutions emerge, ports often face the complexity of navigating a rapidly changing landscape, where regulatory compliance and technological advancements may sometimes be at odds.

Against this backdrop, it becomes useful to take stock of published literature and real-world practices, as they can provide useful insights into the technologies being proposed and applied, the issues emerging in their application, and map the landscape of the ET in ports. To this end, as part of the Horizon 2020-funded MAGPIE project, we carried out an in-depth analysis of 12 European sea- and inland- ports (listed in Table 1) [4], with no difference between the two groups. These ports, considered pioneers in terms of ET and sustainability, were studied through secondary data sources and interviews. This paper offers a review of the current state of knowledge regarding ports and their role in the ET, focusing on best practices, challenges, and potential pathways forward based on the conclusions of the analysis of the ports.

2 Ports and the Energy Transition

This study identifies a lack of comprehensive approaches to the ET in ports. Existing information is often fragmented and filled with promotional and technical language. Three key interconnected themes, however, emerge that can help in making sense of what the ET means in ports and taking stock of the sustainable and greenhouse-gas-neutral initiatives within ports: **ET infrastructure and technologies (ETIT)**, **seagoing ships and hinterland transport services (SHT)**, and **governance for ET**. In addition, electrification is often the first step in the energy transition strategies adopted by ports, and this was observed also in the ports studied. Table 1 summarises the findings for each port in relation to ETIT, and SHT. For governance, it was not possible to differentiate among ports as new governance models for the ET are still being explored. Each theme is discussed briefly in the remainder of the paper.

Table 1. An overview of energy transition measures in 12 European Ports.

Port	Energy transition infrastructure and technologies (ETIT)									Seagoing ships and hinterland transport fuels (SHT)							
	Electrification	Wind	Solar	Tidal	Wave	Biomass	Geothermal	Nuclear	WtE	Ammonia	Biofuels	Ethanol	Hydrogen	LNG	Methanol	Oil-based	WtF
DeltaPort	■									■	■		■			■	
HAROPA PORT	■					■		■	■	■	■	■	■	■	■	■	■
Port of Antwerp-Bruges	■	■	■	■		■	■	■	■	■	■		■	■	■	■	■
Port of Barcelona	■	■	■		■	■			■		■		■	■	■	■	
Constantza Port	■	■	■					■						■	■	■	
Port of Duisburg	■	■	■							■	■		■	■	■	■	■
Port of Esbjerg	■	■				■			■	■	■		■	■	■	■	■
Port of Hamburg	■	■				■	■	■	■	■	■		■	■	■	■	■
Port of Rotterdam	■	■	■			■			■	■	■		■	■	■	■	■
Port of Sines	■	■	■	■						■	■		■	■		■	
Valenciaport	■	■	■	■	■					■	■	■	■	■	■	■	
Port of Venlo	■	■	■			■	■			■	■		■	■		■	■

Notes: WtE: Waste to energy; WtF: Waste to fuel; Oil-based fuels (e.g., Marine gasoil, diesel, etc.) do not include biofuels; Liquified Natural Gas (LNG) includes biogas; Ammonia, hydrogen, and methanol include all production pathways (grey, green, blue, etc.) | Source: [4]

3 The Energy Transition Infrastructure and Technologies

ETIT can be defined as the processes and hardware involved in the production, storage, and distribution of (renewable) energy resources and low- and zero-carbon energy vectors and e-fuels in ports. It includes the development of renewable energy sources, such as solar or wind, as well as the implementation of energy-management technologies, such as smart grids and energy storage systems. This can also include **Carbon Capture and**

Storage (CCS) or **Use** (CCU) to reduce carbon emissions further. The ET infrastructure consists of three main elements: power generation, electrification and grid management, and production of low- and zero-carbon energy vectors and fuels.

Ports are increasingly turning to renewable energy sources as part of their commitment to sustainability and reducing carbon emissions. Among the diverse renewable energy options being explored in ports are **wind**, **solar**, **biomass,** and **waste to energy** (WtE)**.** Other sources of power in ports appear less central to the ET, and include **tidal, wave**, **geothermal**, and **nuclear power.**

The feasibility of these energy sources often hinges on cooperation with the power generation industry, funding, land use and availability, with ports needing to balance spatial requirements of energy infrastructure with other operational necessities. While power generation might not necessarily take place at port, the proximity of ports, for example to **offshore** wind farms, can represent an important business opportunity in the port sector. Ports are also considering how to produce sufficient power internally (**energy self-sufficiency**).

Few ports appear to have a comprehensive **energy** management system in place [5]. Such energy management systems are built on a combination of operational, organisational, and technological measures, including batteries. As energy demands increase due to the **electrification of port equipment**, the increasing use of **electricity to power hinterland transport**, and the adoption of **onshore power supply** (OPS) managing energy flows within the port becomes critical. Ports often grapple with the complexity of electrification, the limitations of outdated infrastructure, and financial constraints [6].

Electrification, coupled with renewable power generation, calls for **peak-load reduction** strategies, aiming to manage and reduce energy consumption during high-demand periods. **Smart grid solutions** are needed, offering an intelligent way to manage energy consumption within the port, ensuring optimal usage and distribution of resources. Additionally, the potential of electricity in the production of low- or zero-carbon fuels and the storage of electricity as energy vectors is being explored. These vectors can also serve as fuels for transport equipment and ships, increasing the attractiveness of their production in ports.

Hydrogen is attracting increasing interest and is being explored in various ports as a potential energy carrier, given its clean-burning properties and versatility. **Ammonia**, another potential energy carrier, is also being considered given its potential use as a fuel for certain types of ship engines [7]. **Methanol**'s appeal is more related to its use as a fuel. The more general concept of **Power to X (P2X)** refers to the conversion of electrical power, primarily from renewable sources, into various forms of energy or products. In the context of ports, P2X can be applied to produce green fuels, store energy, reduce emissions, and create new economic opportunities.

Ports can play an important role in the handling and production of **biofuels**, as **circularity** gains traction [e.g., 8], although they are generally not directly linked to the production of renewable energy. The concept of converting **waste to fuel** (WtF) is also being explored in some ports, providing a renewable energy solution, and addressing the challenges associated with waste management. With increasing demand for low- and zero-carbon energy, it is likely to see that low- and zero-carbon energy vectors and fuels will be increasingly traded, enhancing the role of ports as **logistics hubs** for these products.

4 Shipping and Hinterland Transport Services

Ports are central nodes in transport networks and leveraging on building ET infrastructure at ports can facilitate or even drive the ET in the transport modes that connect at the port. This transition primarily relates to the production, storage, distribution, and provision of e-fuels and electricity. As outlined above, there is an increasing interest in the production, storage, and distribution of e-fuels in ports, and this can build on the role that ports already play in refuelling and bunkering. Yet, without a clear regulatory framework, there is limited proof that ports can significantly impact the fuel decisions of transport and shipping service providers. This positions port authorities more as enablers, facilitators, and coordinators rather than primary agents for the ET in transport.

Ports are central in bunkering operations, although most bunkering activities today still involve **fossil fuels**. There is emerging demand for **methanol** and considerable investment has been undertaken in the transition towards **liquified natural gas** (LNG). Bunkering operations for other types of alternative fuels, such as **biofuels** and **e-fuels** are still at an experimental level [9]. Port authorities, however, are making plans to accommodate bunkering with low- and zero-carbon fuels. The development is likely to be gradual and be guided by the position these fuels with have with the shipping sector, with the possible coexistence of various alternative fuels in the same port.

The central position of ports in global transport networks offers an opportunity to accelerate the transition of hinterland transport modes towards more sustainable practices. **Intermodality** has emerged as a key strategy and is often linked to **modal shift**, which is the transitioning from one mode of transport to another to achieve greater energy efficiency and reduce carbon emissions [10]. As **energy supply systems** within ports and in their proximity are also undergoing significant transformations, they provide a low-carbon energy supply for hinterland transport operations, that will allow for electrification. This is coupled with the provision of **biofuels** and **e-fuels** at ports for land transport modes. Optimising hinterland transport modes—including railways, road transport, inland waterway transport, pipelines, and electricity transmission cables in line with sustainable practices—can further enhance the energy efficiency of the entire transport chain.

5 Energy Transition Governance

Central to the ports' ET is governance, which ensures that strategies align with overarching sustainability objectives and provides a structured framework for transition, directing ports to incorporate renewable energy, enhance operations, and cut emissions. The transition governance is influenced by both **internal** and **external factors**. Internally, the benefits of sustainable operations, such as operational efficiencies and cost savings, are main drivers. Externally, regulatory mandates from governmental and international bodies, along with societal pressures from nearby communities, guide ports towards sustainable practices. **Stakeholder** collaborations, like those between port authorities, shipping firms, and energy suppliers, have fostered renewable energy initiatives within ports. ET can also benefit society by increasing human capital and facilitating new job creation and training, which contribute to a port's licence to operate.

The choices made in terms of ET governance have consequences on the ET. Moreover, ET can influence port competitiveness in the global market. Ports that successfully integrate sustainable practices might find themselves at an advantage, attracting businesses that value sustainability. Conversely, ports that lag behind in their transition might face challenges, especially in regions with stringent environmental regulations.

6 Concluding Remarks

Ports are critical to the ET due to their strategic position, energy consumption, and nearby industrial activities, and those located in the vicinity of power facilities, chemical clusters, or offshore electricity installations are likely to benefit most from this shift. Our review identified three main themes for the ET in ports. In terms of ETIT we showed that the ET so far has been mostly characterised by pilots and planning. The ET in ports mostly concerns renewable power, energy efficiency, and alternative fuel distribution. SHT are still dominated by fossil fuels, with ports acting mostly as enablers. On governance, our review showed that it remains an important challenge together with funding. Projects like MAGPIE accelerate this transition by promoting international cooperation, knowledge sharing, and the development of real-world technical solutions.

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Demonstration of Greenhouse Gas Reductions from Kamsarmax Bulk Carrier Using a Combination of Technologies

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Abstract. International shipping is responsible for around 3% of global anthropogenic greenhouse gas emissions. In order to follow the well below 2-degree temperature goal set out in the Paris Climate Agreement, international shipping must find a solution for decarbonisation in the coming decade, to enable ships that are built in the near future to sail with net-zero emissions around 2050. EU Horizon 2020-funded Project CHEK demonstrates two first-of-a-kind vessel concept designs, based on real operational profiles, to reduce greenhouse gas emissions by 99%, achieve at least 50% energy savings and reduce black carbon emissions by over 95%. This paper focusses on one of the demonstrator vessels, a Kamsarmax bulk carrier. The preliminary results in terms of greenhouse gas emission reductions and energy savings achieved by the combination technologies are presented herein. The technologies comprise wing sails, hull air lubrication, ultrasound anti-fouling technology, route optimisation, gate rudder, flexible drive train using liquid biogas engines with waste-heat recovery in combination with a controllable pitch propeller. Preliminary results show that almost complete decarbonisation is possible, with upcoming full-scale tests and verifications currently in progress during the second half of 2023. The findings of this work build the foundations for the development of the Future Proof Vessel Design platform, a digital tool for design of vessel and operations.

Keywords: demonstration · greenhouse gas reduction · wind-propulsion · alternative fuels · energy savings

1 Technologies Introduced to the CHEK Bulker

The CHEK technologies in the Bulker case consists of wing sails, hull air lubrication, ultrasound anti-fouling technology, route optimisation, gate rudder, flexible drive train using liquid biogas engines with waste-heat recovery in combination with a controllable pitch propeller. The Performance of the technologies are validated through simulation, laboratory testing and/or full scale testing onboard several vessels. The data of these verifications are collected into Deltamarin's (one of the CHEK project partners) *Future*

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Proof-Vessel design platform, in which different combinations can be compared and the most suitable design selected when it comes to emission (and energy consumption) reduction.

A Kamsarmax sized bulk carrier was used as a reference hull for this project. Kamsarmax bulkers have standardized basic parameters with rather similar hull forms. Nevertheless, during the generation of the baseline hull for the project CHEK, improvement potential between 2,2% to 5,5% in propulsion power were recorded [1]. The ship design for this particular bulk carrier has been developed by Deltamarin and the basic particulars of it are presented in Table 1.

Table 1. Basic particulars of Kamsarmax bulk carrier in project CHEK from *Krishnan et al.*

Length overall (LOA)	229.00 m
Length between perpendiculars (LPP)	225.06 m
Breadth	32.26 m
Deadweight and draft	80900 MT at 14.475 m
Laden- service speed and shaft power	14 knots at 80% MCR

1.1 Main Propulsion

Wind Propulsion. Fixed sails can use the wind to replace some of the required propulsion power onboard. Savings are naturally highly dependent on the wind conditions in which the ship operates. When integrating flexibility to the operation and the remaining propulsion system, the use of wing sails are a viable option as energy savings can be made in almost all weather conditions.

The CHEK project included the installation of one fixed wing sail another one was agreed to be installed by charterer, owner and sail provider – BAR Technologies. The span and chord of the sail is 37.5 m and 20 m respectively, Fig. 1. To accurately predict the savings of sails a 4DOF analysis of the ship must be done as well as conducting a force balancing optimization routine to determine the yaw, heel moments, thrust and leeway of the ship. Extremely valuable information has been collected since late August 2023 when the Pyxis Ocean started operation with the above mentioned sails. Data confirming and fine tuning the models should be available during Q1 2024.

Fig. 1. Pyxis Ocean August 2023, courtesy of Cargill

Remaining Propulsion. The remaining propulsion simulation consists of three different propulsion configurations. For simulations with 2-stroke engine the MAN engine 5S60ME-C8.5 PL-EGB (8800 kW) was used. Wärtsilä's W8V31 engine (5200 kW) was employed when a 4-stroke engine was used and MDO was considered as the primary fuel. Conversely, Wärtsilä's W8V31DF engine (4800 kW) was chosen for applications where a 4-stroke engine was utilized, and LBG assumed as the primary fuel [2].

The 2-stroke engine configuration with fixed-pitch propeller represents a typical baseline machinery for the bulk carrier. Figure 2 illustrates a fuel-flexible 4-stroke engine machinery with shaft generators mounted on gearbox and a controllable-pitch propeller (CPP). The digital twin stage will include this aspect and also include the CPP efficiency. For the simulations for digital master, a fixed loss of 1% was included for the shaft line and 2% additional losses due to the gearbox in the 4-stroke machinery.

In all machinery configurations the exhaust gas heat is recovered from the main engines, but not from the auxiliary engines. In the 4-stroke configuration also the engine high temperature cooling water is assumed to be available for selected ship heat consumers and the heat-to-power conversion.

The idea of replacing the industry standard 2-stroke fixed pitch propeller drive train with two 4-stroke controlled pitch propeller drive train is to increase the operational flexibility as the wind propulsion varies according to wind conditions. When the wind propulsion becomes great enough the fixed pitch 2-stroke solution will be outside its operational envelope and little if any gain remains.

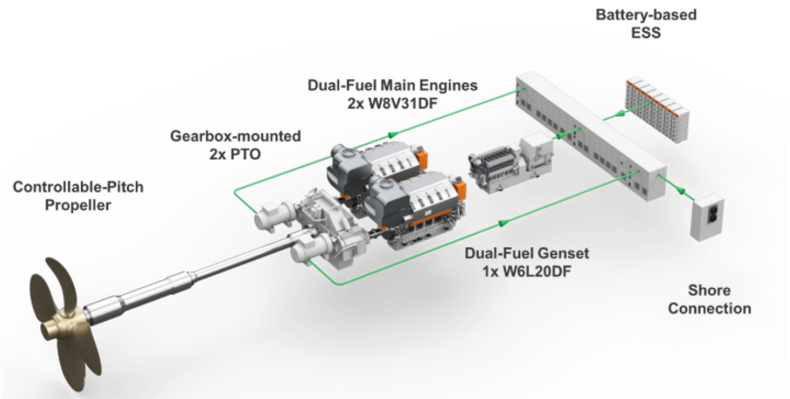

Fig. 2. 4-stroke fuel flexible engine configuration including batteries and shore power. [Reproduced with permission from Wärtsilä, copyright Wärtsilä, 2024]

1.2 Energy Saving Devices

Batteries. In the simulation model the battery's main functionality is to enable higher engine load points, closer to 90–95% instead of the traditional 60% load before additional engine kicks in. Reason being that the efficiency of a low-pressure gas engine increases at higher engine loads. The battery acts as a spinning reserve, compensating for short term load spikes. It is assumed that main engines are allowed to run at 100%, supplying power to the propulsion shaft and shaft generators when the battery is installed. Without batteries, shaft generators are disabled when main engines reach 90% load and auxiliary generators take over.

Waste Heat Recovery. Organic Rankine cycle (ORC) unit is a low-temperature heat engine, that convert heat into electricity. The electricity produced from the waste heat reduces loads on the main engines and thereby fuel consumption as well as emissions.

The working principle of ORC is similar to a traditional Rankine cycle. Where pressurized water is evaporated and expanded through a steam turbine. The main difference compared to the Rankine cycle is that ORC uses an organic fluid as working fluid instead of water. Climeon's laboratory test results are used to feed HeatPower 300 data into the Future-Proof Vessel design platform. The ORCs is connected to a separate waste heat recovery loop, which collects energy both from the engine's HT cooling water as well as exhaust heat through a steam booster.

Air Lubrication System (ALS). Air Lubrication Systems can save up to 10% net fuel consumption and emissions. An Air Lubrication System reduces frictional resistance of the hull by creating a carpet of microbubbles. The system works in all sea conditions, is not weather dependent and does not have a negative impact on the normal operational profile [3].

Air lubrication was modelled according to preliminary estimates of gross power savings as a result of the drag reduction achieved and electrical power demand needed to run the system, provided by the company Silverstream Technologies for the Silverstream® System, during project CHEK.

Ultrasound Antifouling System. The innovative Ultrasound Antifouling Technology "Dynamic Biofilm Protection Intelligent®" by HASYTEC prevents biofouling and marine growth in various marine applications, such as propellers, pod drives, bow/stern thrusters, sea water cooling systems and freshwater generators. Systems and coatings which release biocides and/or heavy metals into the oceans can be replaced in an environmentally friendly and sustainable way.

A non-toxic and environmentally friendly alternative for biofouling prevention is the use of acoustic waves in the ultrasound frequencies (>20 kHz). Such a biofouling prevention system usually consists of a signal generator, a power amplifier and an array of piezoelectric transducers which excite the solid structure.

The above describe technology is ongoing field tests and the preliminary results are very encouraging.

Gate Rudder. A gate rudder, Fig. 3, provides additional thrust and enhanced maneuverability to the ship. This leads to a reduced fuel consumption and to ability of maintaining a set course. The reduction in fuel consumption depends on the vessel type, its operational profile as well as the reference propeller and rudder [4].

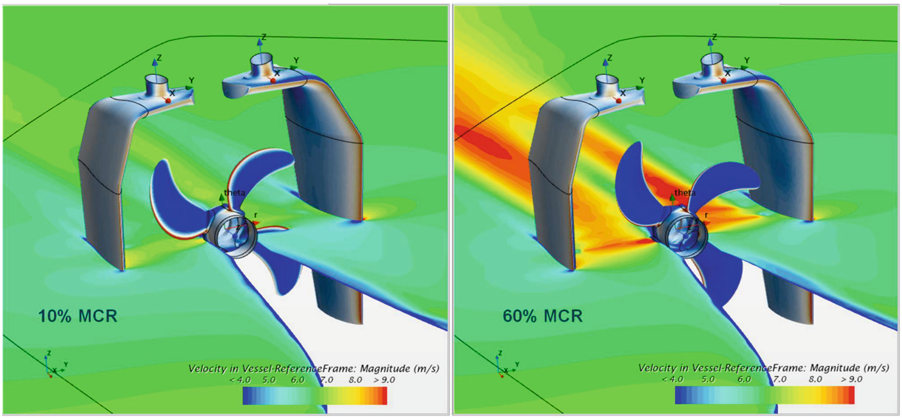

Fig. 3. Gate Rudder [Reproduced with permission from Wärtsilä, copyright Wärtsilä, 2024]

Operations. Introduction of wing sails adds the weather variable in a similar manner as it did a hundred years ago. Wind propulsion combined with constantly updated weather reports, route optimization will give an opportunity to save energy.

2 Conclusions

Once several energy saving applications are combined into the ship design, the total energy saving against the baseline is less than the sum of the saving figures from each individual change. The reason for this is also the numerous interconnections between processes, which are present also when simulating individual changes. For instance, the sails reduce alone the ship engine loads considerably, which results in less waste heat available for the ORCs. Modelling the simultaneous impact of various technologies, even on a rough level regarding some of the technologies, gives valuable insight into projected environmental performance of the ship.

These results of the CHEK project, so far, provides a small outlook into the benefits and necessity to evaluate various technologies and design choices not only from the naval architectural point of view, but also from energy system perspective, assessing the holistic impact of various technologies operating simultaneously on a realistic operational profile. Once the project CHEK is concluded, we can take some learnings from the accuracy of the early stage digital modelling results compared to models supported by latest measurements from laboratory tests or ship onboard measurements.

The preliminary results used in the simulation for the CO_2 reduction of the CHEK Bulker concept indicates a +98% reduction.

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Enhancing Energy Efficiency of Ship Propulsion Systems Through Tubercle Assisted Propellers: A Full-Scale CFD Study

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Abstract. This paper investigates the potential of integrating biomimetically inspired tubercles into ship propulsion systems, specifically ducted propellers, to improve energy efficiency and reduce the environmental impact of maritime transportation. The current study aims to assess the impact of tubercle integration in ducted propellers for analysing the self-propulsion of full-scale ships.

First, computational fluid dynamics (CFD) models and empirical formulas implemented in NavCad are used to compute the ship resistance, showing good agreement in the calculated results. Then, the initial propeller geometry is optimised, considering propeller efficiency and safety aspects related to cavitation and noise limitations. By applying the concept of tubercle-assisted propellers (TAP), CFD simulations are conducted to analyse the self-propulsion performance of a ship equipped with a tubercle-adapted propeller. The results are compared with previous tubercle studies to discuss the effect of tubercles on self-propulsion performance.

Keywords: Computational Fluid Dynamics (CFD) · Tubercle Assisted Propellers (TAP) · Full-scale · Self-Propulsion · Energy-Saving Devices (ESD)

1 Introduction

The propulsion system is one of the main important aspects of reducing consumption; therefore, the different parts of the system have been improved and optimised over the years towards improving energy efficiency [1, 2]. These improvements are applied to the prime mover as the main component of the propulsion system [3, 4]. Also, the propeller has been improved and modified for each ship to increase efficiency, reduce cavitation and operate at a lower operating point, thus reducing fuel consumption. Looking at the ocean, humpback whales are remarkable marine mammals. Despite their large size, they can move quickly and skilfully to catch their food. This is attributed to the presence of

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large bumps, known as leading-edge (LE) tubercles, on the leading edge of their pectoral fin. Tubercles act as passive flow control devices and have found applications in various fields, including hydro/aerofoils, rudders, and tidal turbines. They have been shown to improve hydro/aerodynamic performance in stall conditions, reduce noise, and prevent cavitation [5]. Researchers at the University of Strathclyde and Newcastle University performed an investigation to apply the concept of tubercles to marine propulsors. It is known by Tubercle Assisted Propellers (TAP) and is considered one of the energy-saving devices (ESD) by optimising and developing the concept on both duct and propeller applications [6–8]. This paper builds upon previous work by applying a novel concept to the propulsion system of a multipurpose service vessel in the offshore field. This study presents the preliminary results of numerical computations and propeller design.

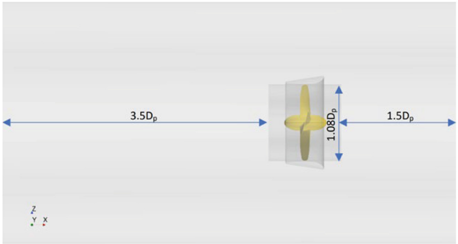
2 Numerical Study

2.1 Target Vessel and Resistance Simulations

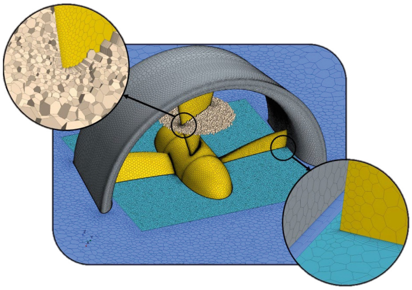
Fortuna Crane is one of the service vessels operated by O.S Energy [9]. As part of the project, the propulsion system will be enhanced. The existing propellers will be replaced with tubercle propellers with ducts. Reynolds Averaged Navier-Stokes (RANS) method is used with the Shear Stress Transport (SST) k-ω turbulence model for the RANS closure. In resistance and self-propulsion simulations, a computational domain with the dimensions of $-3L < x < 2L$, $-L < y < L$, $-L < z < 0.8L$ is used, where L is the length of the ship. In resistance and self-propulsion analyses, the computational domain is discretised with unstructured trimmer cells, while polyhedral cells are used for the open water case. The free surface is modelled with the Volume of Fluid (VOF) method. The average wall y+ values are kept around 50 for all speeds. The validation study is conducted with a monohull research vessel model, Prince Madog, with a scale of $\lambda = 8.4$ since the experimental results are available. Computational fluid dynamics (CFD) overestimates the resistance by 9% at 11 knots, while a good agreement is seen at lower speeds. Besides, the well-known benchmark model, KRISO Container Ship (KCS), is used for the second validation case. The percentage differences in terms of total drag for the validation cases vary between 2% and 9% along the speeds.

2.2 Open Water Simulations

Open water numerical simulations are performed by using cylindrical regions: static region and rotating region with diameters of 1.5 D_p and 1.08 D_p, respectively, where D_p is the diameter of the propeller. The computational domain can be seen in Fig. 1(a) including the nearfield rotating region around the propeller. Polyhedral cells are used for the discretisation of the computational volume. A detailed view of the grid is given in Fig. 1(b). The propeller is kept in the rotating region, while the duct is kept in the static region. The moving Reference Frame (MRF) method is used to simulate the propeller rotation. The average wall y+ values are kept under 5 in these simulations.



(a)



(b)

Fig. 1. (a) Computational domain for the open water simulations, (b) Discretization details around the propeller and duct. Source: Proprietary software (Simcenter STAR-CCM+)

2.3 Self-propulsion Simulations

In this study, self-propulsion simulations are performed both with the virtual disk method and with the propeller geometry. The virtual disk model is based on the principle of representing propellers, turbines, rotors, fans, and similar devices as an actuator disk. This treatment is practical when the focus is on understanding the impact of rotor/propeller behaviour on the flow rather than the detailed interactions between the flow and the blades of the rotating device. At first glance, the virtual disk model is preferred due to its cost effectiveness in simulations. The results of the simulations using the virtual disk method are used to estimate the coefficients of thrust deduction and wake fraction for the entire speed range of the vessel. This information sheds light on the new propeller design. The self-propulsion simulations with the virtual disk method are performed using the same mesh and physics properties as the resistance simulations. Following the new propeller design, free running self-propulsion simulations with the propeller geometries are conducted for both propeller cases: the reference propeller without tubercles (a 4-bladed Kaplan with 19A duct) and the TAP propeller (the reference propeller with tubercles) with duct. A 5-s ramp condition is employed to reach the desired propeller rate of rotation for better convergence. The simulations are carried out using a 3DOF setup, including surge, heave, and pitch.

2.4 NavCAD Simulations

NavCad is a simulation tool that focuses on predicting and analysing the power requirements of a ship at different speeds. Firstly, the tool calculates the total resistance of the ship using Holtrop methods, showing a good agreement with the resistance computed from the CFD model, as shown in Fig. 2. This step is used for the validation purposes of the two software. Therefore, the resistance components from the CFD model are implemented in NavCad, as well as the propulsive coefficients and the propeller has been selected and designed for the given design speed as well as the engine layout. Then, the geometry of the Kaplan propeller with a 19A duct is sized.

3 Results and Discussion

3.1 Ship Resistance

The numerical frictional coefficients (C_{FS}) computed from the CFD model are compared with the ITTC formula along different speeds, and Fig. 2(a) shows a good agreement between the numerical and empirical values. Similarly, the total resistance (R_{TS}) values are compared with the results obtained using the NavCad (Holtrop and Mennen Method), as shown in Fig. 2(b), and they also exhibit good agreement.

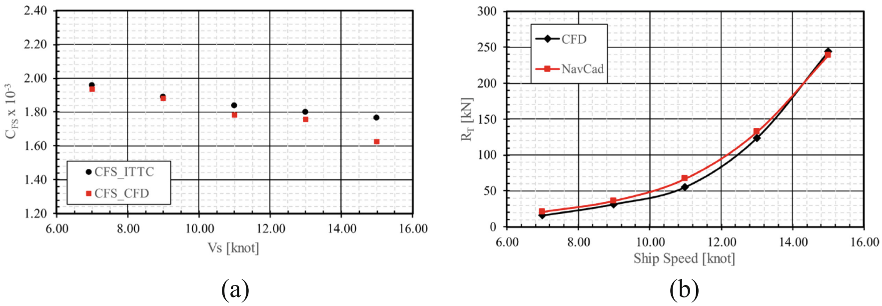


Fig. 2. (a) Comparison between the frictional coefficients from the CFD model and ITTC, (b) Comparison between the total resistance computed from CFD and NavCad along different speeds.

3.2 Propeller Design

Through extensive numerical simulations, an optimal propeller design is developed targeting maximum efficiency while meeting noise and cavitation limits. The propeller geometry and operating point are carefully selected and optimized using data from CFD analyses and NavCad. Key parameters like pitch, expanded area ratio, and diameter are fine-tuned to achieve the highest possible open water efficiency of 56% for the operating conditions. To generate the 3D propeller, we utilize our in-house code modified based on OpenProp, incorporating the optimized sections shaped by the comprehensive simulations. This results in an efficient four-bladed Kaplan propeller with a pitch diameter ratio of 0.96 and expanded area ratio of 0.55. The propeller curve aligns well with the engine load diagram, indicating satisfactory performance across speeds. The main parameters of the propeller are computed, and the newly designed Kaplan 4-bladed propellers can be seen in Fig. 3.

3.3 Self-propulsion Simulations

The effect of tubercle-adapted propellers on ship propulsion systems is investigated through free running 3DOF CFD simulations. Two simulations are conducted, one with a TAP and one without a tubercle propeller design, starting from zero speed and accelerating with the thrust force generated by the ducted propellers. The results are presented

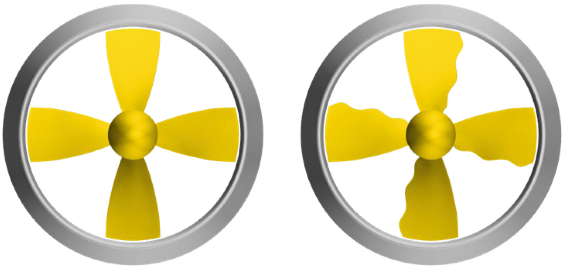


Fig. 3. Newly designed KAPLAN propellers, reference propeller on the left-hand side, TAP on the right-hand side. Source: Figure produced using OpenProp, an open source software.

in Fig. 4(a). Initially, it is observed that the TAP provides a higher thrust force and results in a greater initial acceleration compared to the reference propeller without tubercles. However, after 130 s of simulation, the ship with the reference propeller achieved a higher speed than the one with the TAP design, as can be seen in Fig. 4(b). The achieved results suggest that the tubercle adaptation to the propeller increases thrust at low speeds but may have limitations in achieving higher speeds.

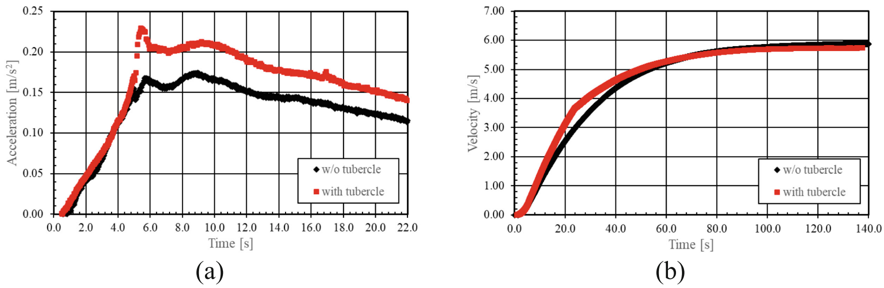


Fig. 4. (a) A comparison of acceleration in x direction for different propeller designs, (b) A comparison of the obtained velocity for the free running ship models.

4 Conclusions

The paper presents a comprehensive computational study analysing the potential benefits of integrating biomimetic tubercles into ship propulsion systems. Resistance, open water, and self-propulsion simulations are conducted using CFD to evaluate the performance of tubercle-assisted propellers (TAP) in full-scale conditions. The key findings suggest that TAP can provide higher thrust at lower speeds compared to conventional propellers, resulting in greater acceleration. However, at higher speeds, limitations appear, and conventional propellers achieve faster equilibrium speeds in self-propulsion simulations. Overall, the results demonstrate the promise of TAP in improving thrust and efficiency at low speeds. Further research is still required to fully understand the trade-offs at higher speeds and optimise tubercle designs for maximum performance across operating ranges. Additional analysis of hydrodynamic efficiency, power consumption, and cavitation behaviour is recommended.

Acknowledgement. This work has been conducted under the RESHIP project. This project has received funding from both the European Union's Horizon Europe research and innovation programme (Grant agreement: 101056815) and the Innovate UK's Horizon Europe Guarantee scheme (Ref: 10052906, 10051800, 10059974).

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Development of Energy Efficient Solutions for Hydrogen Powered Vessels: RESHIP Project

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Abstract. RESHIP project funded under the Horizon Europe programme aims to redefine energy efficiency for using hydrogen for ships with disruptive technologies in Energy Saving Devices (ESDs) and onboard hydrogen system for a seamless transition towards zero-emission. The project focuses on two key technologies, the Tubercle Assisted Propulsors (TAPs) and the liquid inorganic hydrogen carrier, HydroSil. TAPs technology is based on a novel and generic biomimetic passive flow control mechanism inspired by humpback whales, which have small bumps on their pectoral fins known as leading-edge (LE) tubercles. The research shows an improvement in the propeller efficiency, constrain the cavitation development and reduce the underwater noise level. HydroSil is an innovative patented liquid inorganic hydrogen carrier with a long storage life, stable, non-toxic, non-explosive and non-dangerous. This highly energy-efficient hydrogen carrier makes the solution cost-effective, with up to 40% savings due to the reduction in capital and operational expenditure.

Combining the features of the above two technologies, RESHIP aims to develop a prototype to be trialled at sea using the project target vessel, the Fortuna Crane, owned and operated by O.S. Energy. The project will analyse the results and reflect on the wider applications for sea-going and inland vessels.

Keywords: RESHIP · HydroSil · Hydrogen Carrier · Tubercle Assisted Propeller · Energy Saving Devices

1 Introduction

Several actions have been taken to reduce Greenhouse gases (GHG), improve the energy efficiency of the ships and meet the requirements of decarbonisation in shipping [1, 2]. The taken actions covered the different ship parts to take benefit of the optimization of each part and achieve the maximum improvement in energy efficiency.

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One of the most essential solutions suggested is fuel selection, as it directly impacts the reduction of exhaust emissions from the prime mover of the ship [3]. Utilised as an alternative fuel, hydrogen offers an appealing resolution for achieving forthcoming objectives set by the International Maritime Organization (IMO), and it is regarded as a feasible contributor within the context of a future vision for environmentally friendly shipping. In addition, hydrogen can be used to generate other types of fuels such as ammonia, providing higher flexibility to generate different types of green fuels [4].

Taking the United Kingdom as an example, the 'balanced pathway' scenario of the Sixth Carbon Budget established by the Climate Change Committee envisions the substantial growth of green or blue hydrogen by 2035, reaching a capacity equivalent to almost one-third of the current power sector. This hydrogen would find applications in areas less suited to electrification, notably within certain segments of industry and shipping [5]. Shortly, hydrogen could play an important role in marine transportation, used alone to produce electricity or in addition to conventional or biofuels in internal combustion engines.

In addition to hydrogen as a promising fuel in marine applications, the significance of energy-saving devices (ESDs) for ships has grown substantially due to the enforcement of rules and regulations that limit the utilisation of fossil fuels and encourage the adoption of zero-emission technology [6].

Therefore, the RESHIP (Redefine energy Efficiency solutions for hydrogen powered SHIPs in maritime and inland transport) project aims to redefine onboard energy-saving solutions with disruptive technologies in ESDs and onboard hydrogen management to propose a hydrogen-compatible solution for a seamless transition of zero-emission marine and inland shipping.

This project aims to enhance energy efficiency performance and address the current challenges for hydrogen usage onboard, including high energy demand, abrupt power spikes, and demanding energy storage requirements.

The project targets two distinct research topics; hydrogen-compatible ESDs and energy-efficient hydrogen onboard utilisation. The combination of both research outcomes will demonstrate a next-generation hydrogen power and propulsion system for zero-emission waterborne transport.

The consortium[1] gathers world-leading multidisciplinary experts with key patent holders from both the shipping and hydrogen sectors, forging a complementary stakeholder group. The implementation of the developed technologies will be validated at technical, environmental, cost economic, safety and regulatory levels to propose tailored solutions for newbuilds and retrofits in marine and inland waterways.

[1] https://www.reship-project.com/, HySiLabs (HSL), H2TEC BV (H2T), Chalmers tekniska högskola AB (CTH), DST Entwicklungszentrum für Schiffstechnik und Transportsysteme e.V. (DST), Consiglio Nazionale delle Ricerche (CNR), Glafcos Marine EPE (GME), Danaos Shipping Co Ltd (DANAOS), Bureau Veritas Marine & Offshore (BV), Baumüller Anlagen-Systemtechnik GmbH & Co. KG (BAS), Esbjerg Shipyard A/S (ESB), University of Strathclyde (UoS), Newcastle University (UNEW), Stone marine propulsion limited (SMP) and O.S. Energy (UK) Ltd (OSE).

2 Energy Saving Devices and Tubercle Assistant Propulsors Technology

As required by the vessels' operation profile and the capability needed to handle manoeuvring and high sea states, the propulsion loads vary significantly between particular situations, which also causes significant power fluctuation leading to damages to fuel cells and hydrogen supply systems. ESDs improving propeller flow conditions and reducing vessel motions help reduce shaft power fluctuation and are favored for hydrogen-powered vessels [6].

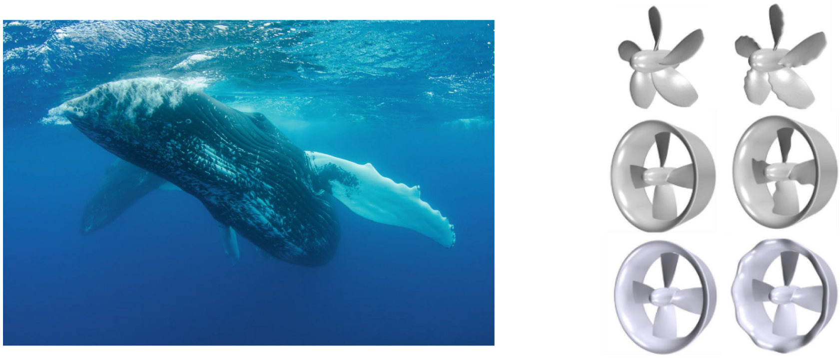
RESHIP aims to develop hydrogen-preferred ESDs with a minimum of 10% energy saving in a single application and 20% in combination. The project develops technology around Tubercle Assistant Propulsors (TAP), which offers a wide application for marine and inland vessels with energy saving, cavitation limitation and noise mitigation features; meanwhile, it also offers smoother shaft power delivery due to mitigated sudden stall and constrained cavitation development [7].

TAPs technology, as shown in Fig. 1, is based on a novel and generic biomimetic passive flow control mechanism inspired by humpback whales. They have small bumps on their pectoral fins, known as leading-edge (LE) tubercles, which aid in their ability to perform acrobatic manoeuvres to catch prey. The concept is initially believed to be able to control flow separation due to energised flow being more attached to the surface. Recently, through detailed aerodynamics, aeroacoustics and hydrodynamics studies, this concept has shown further capabilities in improving the aero/hydrodynamic performance of various applications, constraining cavitation development and mitigating noise. Researchers at UoS and UNEW have investigated the application in-depth on marine propulsors, driving the initial design, optimisation and analysis phase and developing the concept on both duct and propeller applications [6–9]. Their work provides valuable input for the design of future marine vessels and retrofit solutions for existing builds, where improving energy efficiency and reducing ship fuel consumption and carbon emissions are major concerns.

3 Hydrosil and Efficient Hydrogen Carrier

The big challenge that currently hinders the deployment of hydrogen as a real solution for carbon-free, efficient mobility is how to transport and store it in a safe and economic way. The ideal solution for mass delivery has to (1) be a liquid, to take advantage of the existing fossil fuel infrastructures, (2) be non-dangerous and stable to be easily and safely handled, (3) contain high hydrogen density and (4) be cost competitive. Hydrosil is an inorganic liquid hydrogen carrier developed by HSL technologies (formerly Hysilabs) [10]. It shows a hydrogen gravimetric content of 8.7% with a density ratio of around 1.15 and it can store 100 kg H_2/m^3.

To release hydrogen, Hydrosil is mixed with water in the presence of catalysts. The reaction is instantaneous, complete and exothermic, without any energy input. A silicate by-product is formed, which corresponds to twice the initial volume of Hydrosil. This by-product is stored, unloaded at the port and recycled into Hydrosil. The storage space and weight of the by-product are taken into account during the calculations.



(a) (b)

Fig. 1. (a) Humpback Whales "Source: https://www.pexels.com/photo/blue-whale-swimming-under-water-4781925/" and (b) leading-edge tubercle applications on marine propellers [9] "Source: Figure produced using OpenProp, an open source software".

"State-of-the-art hydrogen vessel" is hard to identify since no large scale hydrogen powered vessel has yet been put in service. However, compressed gas (GH_2) is currently the most advanced technology being considered for H_2 usage onboard ships [11]. It has been prototyped on small scale boats [12] and is considered for middle size applications. For this study, the standard GH_2 pressure considered is 350 bars as well as 590 bars as another alternative.

The need for stored energy is calculated taking into account the power of auxiliary generator sets (gensets), main engines, and, finally both, working 24/7 at 100% load for 30 days (maximum endurance of the boat). The corresponding energy amounts respectively to 540, 1,166 and 1,706 MWh. To meet such energy needs, the corresponding storage volumes and weights should be installed.

Based on the data provided, the solution based on Hydrosil would reduce the need for storage space to 25% compared to the use of GH_2 at 350 bars, while an increase in weight is detected by 20%. Compared to GH_2 at 590 bars, the solution based on Hydrosil would reduce the need for storage space to 38%, also the weight will be reduced by 20%.

Hydrosil thus represents an opportunity to drastically limit the storage space and, to a lower extent, the storage weight in comparison with compressed hydrogen. However, even with Hydrosil, the storage volume and weight exceeds the boat's capacity. To accommodate a shift to hydrogen-based energy, the autonomy of the boat would have to be reduced.

Assuming the storage volume could be extended to 600 m^3 by adding storage units on the deck, a total of 317,000 kWh could be stored onboard with Hydrosil, corresponding to 460 t onboard, to be compared to the current 420 m^3 (359 t) of marine gas oil (MGO). This would also mean the boat would have to be refueled 5.4 times more often than with MGO, or that autonomy would be limited to 5.5 days. These figures would be enhanced further with an optimised realistic usage profile of the boat.

4 Plan Demonstration

The suggested solutions in this project will be tested on the target vessel, the Fortuna Crane, one of the service vessels operated by O.S. Energy [13]. The energy efficiency measures proposed by RESHIP are based on two fundamental principles, ESDs, which are mainly based on ship propulsion hydrodynamics and hydrogen focused around a novel hydrogen carrier and its utilisation. Based on the two technologies, RESHIP will focus on demonstrating:

1. Proof of gains in vessel energy performance and operational efficiency through TAPs technology as well as the limitation of torque fluctuation. A comparative sea trials with live torque measurements will be presented before and after the retrofitting procedure. The amount of fuel consumption and loading conditions will be compared to achieve the exact improvement from the retrofit procedures.
2. The feasibility of an HydroSil-powered 50 kW genset, operating it at sea for 6 h as well as the gain in storage space and/or weight. The results will be based on operating the genset during a dedicated sea trial.

Furthermore, wider applications of the combination of TAPs and HydroSil will be studied to identify the most relevant use cases in maritime transport and/or inland navigation.

5 Conclusion

The technologies proposed in RESHIP are novel concepts and need further recognition. RESHIP will provide a concrete demonstration of their potential and provide a set of relevant use cases. Once mature, large-scale application of the solutions proposed in RESHIP would lead to:

1. A safe, clean, low-cost global ocean transportation. The development of the international shipping industry will accelerate the transfer and trading of goods between continents.
2. Enhance the energy utilisation efficiency of the renewable energy industry. The widely used hydrogen fuel will encourage the energy industry to produce hydrogen from the excess power from renewable energy devices as energy storage solutions. The low-cost hydrogen fuel will further promote the application of hydrogen energy.
3. Eliminate the GHG emissions in the ship industry and reduce the carbon footprint of human activities on the ocean.

Acknowledgment. The authors acknowledge the contributions of all RESHIP partners and of numerous researchers who contributed to the work presented herein. RESHIP project has received funding from both the European Union's Horizon Europe research and innovation programme (Grant agreement: 101056815) and the Innovate UK's Horizon Europe Guarantee scheme (Ref: 10052906, 10051800, 10059974).

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Simulation of Hybrid Fuel Cell-Battery Propulsion System Scrutinizing Multi-scheme Energy Management for a CTV Boat

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Abstract. This paper proposes a model of a hybrid fuel cell-battery propulsion system for a Crew Transfer Vessel (CTV). A multi-scheme energy management strategy is also applied to the EMS block to optimize energy flow. A fuel cell-battery hybrid system was developed by integrating PEM fuel cells with Li-ion batteries to provide electricity to the propeller propulsion system, and hotel load. Accordingly, a hybrid battery/fuel cell propulsion system with the capability of both charging the battery at both stations and bunkering the fuel tanks will be proposed. During cruising, docking, stopping, accelerating, and loitering phases of a ship journey, power distribution will be carried out, and energy requirements will be investigated at different EMS strategies with the objective of maximising system efficiency. A simulation using MATLAB/Simulink software is conducted using operational profiles at different power load conditions. Simulation is conducted using four EMS schemes: state-based, equivalent fuel consumption minimization strategy (ECMS), a charge-depleting and charge-sustaining strategy (CDCS), and classical proportional-integral (PI) controller-based, which are all selected based on power mode and battery SOC. Results show proposed multi-scheme strategy can lead to significant energy and cost savings, with a maximum of 4% and 12% respectively.

Keywords: HyShip-Clean Hydrogen · Zero-emission · Crew Transfer Vessel (CTV) · Hybrid Fuel Cell/Battery · Energy Management System (EMS)

1 Introduction

The 'Initial IMO Strategy for Reducing GHG Emissions from Ships' was published by the International Maritime Organization (IMO) in 2018. This plan intends to reduce carbon intensity by 40% by 2030 and 70% by 2050, as well as cut international shipping emissions in half by 2050 [1, 2]. The HySHIP project focus on the development and commercialization of hydrogen fuel and the demonstration of a marine vessel running on liquid green hydrogen (LH2). Maintenance activities are primarily to blame for the majority of the carbon emissions that result from operating wind farms, with shipping accounting for 70% of these emissions. Based on previous studies, one may find Crew

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Transfer Vessels (CTVs) are the primary vessels involved in the operation and maintenance of wind farms [3]. The switch to electric vessels is being encouraged by both wind farm operators and ship owners and new CTV concepts are subject to rapidly employing zero-emission affordable propulsion systems. The required operational conditions of the future-proof CTV concept are expressed below:

- Zero-emission CTV concept by using a flexible hybrid power plant that covers different port infra-structure both hydrogen bunkering and battery recharging
- higher transit speed higher endurance to remain in service for a long time journey
- Energy management strategy (EMS) optimization to improve the electrical integration of the system in different operational situations

Choi et al. [4] conducted a state-based EMS to maximize the hybrid system efficiency of a Korean tourist boat. The required energy flows over the PEM fuel cell and Battery stack provide the required load power by charging and discharging at different power loads. Motapon et al. [5] designed a new approach of a multi-scheme EMS to enhance the performance of hybrid fuel cell systems. The multi-scheme approach switches energy management strategy at different levels of battery SOC and different load modes. Another effort of a multi-scheme approach has been conducted by Bassam et al. [6] applied on an electric-driven passenger ship. They proved the applicability of their developed EMS system by reducing energy and hydrogen consumption by 8% and 16.7% respectively. In addition, some successful demonstrations have been achieved in the past few years for marine applications with FCs [7, 8].

Accordingly, one may conclude that CTV operations need to be developed an efficient low energy-consumed vessel needs to be designed. This flexible environment incorporates the Simscape Power Systems (SPS) toolbox [9] of Simulink environment. The energy management strategy involves the control and distribution of power from FC or battery or simultaneous power source usage in high-demand situations. A proton exchange membrane fuel cell (PEMFC) and Li-ion battery packs are joined in the hybrid system. Proton exchange membrane fuel cells (PEMFCs) get superior benefits in the transportation industry, which are increasingly being used [10–12]. A Battery system is used to hybridize the fuel cell propulsion system to improve the efficiency of propulsion system. When both fuel cell and battery systems are integrated into a hybrid powertrain, Energy Management Strategies (EMS) are needed to allocate the power among different sources while minimizing energy waste overall operation of the hybrid system. Thus, the paper is structured in sections starting with description of the CTV vessel. After that, a power requirement calculation will be implemented to define the approximated operational profile. Finally, a sample voyage of the vessel simulation and the results of different EMS schemes will be discussed.

2 Problem Definition

A CTV vessel has been designed in the Maritime Safety Research Center (MSRC), Strathclyde University regarding appropriate catamaran ship performance on high seas and reaching high-speed capability [13, 14]. This boat has been developed by the HySHIP project, funded by the EU as a decarbonization project. Figure 1 displays a perspective view of the CTV case study. Two PEMFC systems are installed on this ship with a DC-DC converter to stabilize the fuel cell voltage (See Fig. 1). The power requirement of the vessel is divided into two propellers for two demihull of the catamaran and constant on-board auxiliary equipment. Models of the ship's hybrid fuel cell propulsion system and various energy management techniques are created in the MATLAB/Simulink environment. The purpose of the research is to examine the performance of a hybrid system for electric-driven propulsion that combines FC and a battery. An effective, optimal EMS based on operation states is suggested for this case study.

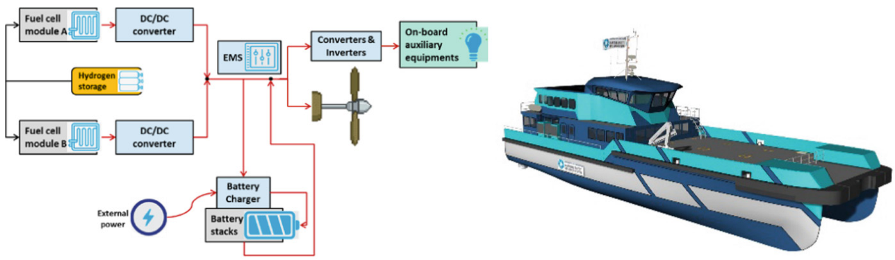


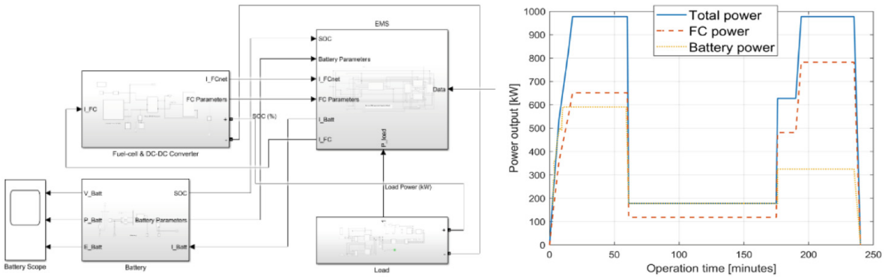
Fig. 1. Crew Transfer Vessel (CTV) case study of Hybrid FC/Battery propulsion system "Source: Authors".

3 Simulation Implementation

The hybrid FC/Battery system of the CTV vessel is modelled herein in four main blocks of Fuel-Cell & DC-DC Converter, Battery stack, EMS, and electric motor load power as shown in Fig. 2 (a). A generalized PEMFC model has been created and integrated into Simulink. Fuel cell stacks are fed with hydrogen and air. The fuel cell stack is modelled by characteristics of 50 kW–625 Vdc that can be obtained from the fuel cell polarization curve. A fully operational 4-h cycle of the examined CTV vessel simulates in the Simulink environment by developing multi-scheme EMS in order to minimize total energy consumption and hydrogen fuel usage of PEM fuel cell stacks. Accordingly, total energy ($Energy_{Total}$) includes fuel cell energy consumption ($Energy_{FC}$), battery depleted energy ($Energy_{Batt}$), and used energy to recharge the battery back to its initial battery SOC ($Energy_{BattCh}$):

$$Energy_{Total} = Energy_{FC} + Energy_{Batt} + Energy_{Batt_{Ch}} \tag{1}$$

The simulation is conducted based on the operational profile that includes docking operations, stopping, cruise and sprint speed. The simulation results are presented in Figs. 3, 4 considering initial battery SOC of 60%. The simulation runs for each EMS scheme separately to compare the performance of the system. A sample test of power output and supplied power from FC and battery is depicted in Fig. 2 (b). The battery system runs in the power chain when the power profile reaches 496 kW and starts discharging approximately one-third of the total power output. Low mode power and high mode power consider 490 kW and 923 kW respectively. Different power output was implemented to evaluate the performance of the system. According to 4 h operations, the value of total energy consumption is calculated and compared in Fig. 3. Accordingly, the Multi-scheme approach consumes less energy than State-based, ECMS, CDCS, and Classical PI by 2.26%, 3.94%, 2.72%, and 0.83% respectively. One may conclude that the multi-scheme technique can reduce energy consumption. The plot depicts the energy usage of the fuel cell, battery and battery recharging to keep it in initial SOC. Battery recharging implements during 2 h loitering of CTV.



(a) (b)

Fig. 2. (a) Hybrid fuel cell/battery power system in Simulink/MATLAB environment. (b) Total power of load, and FC and battery power load for 4 h voyage mission.

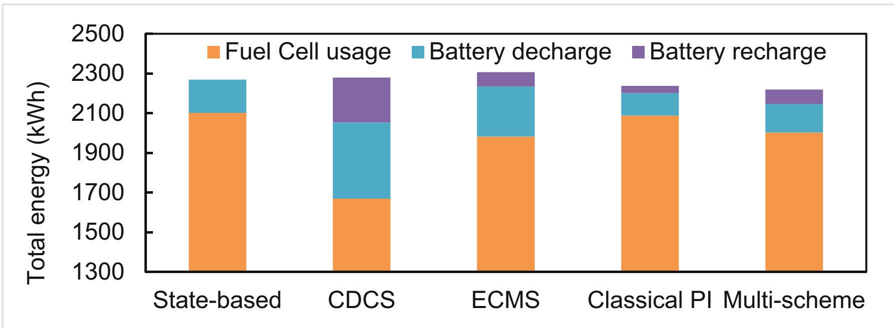


Fig. 3. Total consumed energy comparison in kWh.

Assuming a wind-generated hydrogen cost of $4.823 per kilogram (1 kg of hydrogen produces 33.33 kWh of electrical energy) [15] and an average electricity price of $0.284 per kilowatt-hour for battery recharging using shore-side energy [16], the operational cost for each EMS strategy and multi-scheme one illustrates in Fig. 4 [17]. In terms of the overall cost, the multi-scheme EMS demonstrates a comparable operational cost to other strategies. However, the overall cost of the multi-scheme EMS is marginally greater than that of the classical PI strategy by 0.5%. Besides, the multi-scheme EMS obtains 3.1%, 12.3%, and 8.1% cost saving compared to state-based, CDCS, and ECMS strategies, respectively.

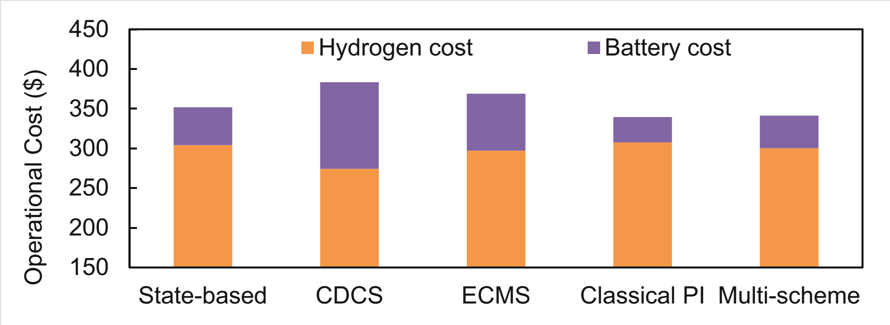


Fig. 4. Total cost comparison in $.

4 Conclusion

The electric-driven ships powered by a hybrid fuel cell/battery system could significantly reduce greenhouse gas emissions and air pollutants that are working in optimized conditions. This paper proposed a hybrid FC/battery power system for a CTV using a multi-scheme EMS system. A simulation model for the components of the hybrid systems is depicted herein, which is conducted in a MATLAB/Simulink environment. The aim of this effort is to find a suitable EMS strategy regarding energy consumption reduction and consequently mitigation of operational costs. The designed multi-scheme EMS has been thoroughly evaluated in comparison to alternative strategies over a complete 4-h operation. The results indicate that the suggested multi-scheme strategy has the potential to yield substantial energy and cost reductions, reaching up to 4% and 12% respectively. The approach can be improved in future works in the case of operational profile optimization to reduce energy consumption and alternative FC and fuel sensitivity analysis.

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Development of Design Configurator Tool for Rapid Initial Design of Fast Zero-Emission Battery-Electric Vessels

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Abstract. Small vessels, such as river buses, ferries, and workboats, have significant decarbonization potential by implementing battery-electric propulsion systems. Designing battery-electric vessels presents unique challenges due to the lower energy density of the battery. The battery constitutes a significant portion of the vessel's weight and space, and it size heavily influenced by operating profiles and availability of charging stations and charging speed. This creates feasibility concerns for pure battery-electric vessels in terms of weight, space, and charging requirements. To address this, a design configurator tool has been developed, which can swiftly generate initial designs of battery-electric vessels and evaluate feasibility based on the specific design and operational requirements. The tool takes design requirements as inputs and outputs include potential design candidates together with various ship design calculations including feasibility and optimality assessments. The design of the tool is based on a hull design database containing various combinations of main dimensions, with the corresponding hydrostatic and hydrodynamic data. The capability of the tool was demonstrated in designing two replicator vessels in the EU Horizon TrAM project. This design automation tool aims to expedite the transition to zero-emission battery-electric vessels by aiding decision-making processes for ship operators and designers, considering their unique operational requirements.

Keywords: battery-electric vessels · design configurator tool · ship design automation · parametric hull model · decarbonization · TrAM project

1 Introduction

Climate change has prompted urgent calls for reducing greenhouse gas emissions across all sectors. Ambitious decarbonization targets have been set both by the International Maritime Organization (IMO) and various governments for the maritime industry [1]. Different decarbonization options are being explored for the different ship types, sizes and operation profiles. Among various vessel types, smaller vessels such as river buses, ferries, and workboats stand out as excellent candidates for decarbonization through battery-electric propulsion systems. These waterborne electric vehicles not only produce

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zero emissions but also offer quieter rides with reduced vibrations. Furthermore, the efficiency of an electric propulsion can be as much as 90% [2]. Although the capital investment costs (CAPEX) are relatively higher, the operational costs (OPEX) can be lower due to the lower energy costs and reduced maintenance. Several pioneering battery-electric vessel projects have emerged worldwide. Notable examples include the MS Medstraum (2022) [3], Bastø Electric (2021) [4], Yara Birkeland (2021) [5], MV Ampere (2015) [6], MS Legacy of the Fjords (2020) [7] in Norway; the Ellen E-ferry (2021) [8] in Denmark.

In comparison to conventional hydrocarbon-fuelled vessels, designing battery-electric vessels presents unique challenges due to the significantly low energy density of the batteries. Since conventional fossil fuels have high gravimetric and volumetric energy, the fuel weight and tank space are not very critical as there is usually enough hull displacement and space for the fuel for most operational requirements. However, in the case of pure battery-electric vessels, the battery units constitute a significant portion of the vessel's weight and valuable space. The total weight and size of the onboard batteries are also heavily influenced by the operating profiles, availability of the charging stations on the route as well as charging duration and speed. This creates feasibility concerns for pure battery-electric vessels especially high-speed vessels, in terms of weight, space, and charging requirements. Minimizing the number of battery units became one of the primary objectives in the design optimization of battery-electric vessels.

Since the vessel dimensions, propulsion system and battery specifications are dependent on the operating profile and onshore charging infrastructure, all those variables need to be simultaneously taken into account during the initial ship design stage. In some cases, building additional charging stations and/or modifications to the operating profile might be required to obtain a feasible solution. To navigate these challenges, this paper introduces a design automation tool, which can swiftly generate design candidates for a battery-electric vessel and evaluate feasibility based on the specific design and operational requirements. By using this tool, ship operators and designers can quickly determine the feasibility of a battery-electric vessel for their specific use case and make decisions for new vessels and required charging infrastructure.

2 Design Configurator Tool

The tool's architecture is based on a design database of hull forms and associated hydrostatic and hydrodynamic (resistance) data for various combinations of main dimensions (Fig. 1). The use of a design database allows to quickly assess the various designs without requiring to generate new geometry and compute hydrostatics and resistance data whenever there are changes in the requirements.

The main inputs to the tool include:

- Vessel's main dimensions either specified by fixed values or ranges
- Operating profile that includes a table of distances or ranges and corresponding speeds
- Operating environment such as fresh or seawater, deep or shallow water
- Propulsion system type: propeller or water and optional efficiency value
- Specification of single battery string unit such as capacity, weight, dimension, as well as depth of discharge (DoD), End of Life (EoL) margin, etc.

- Auxiliary loads

The outputs include the list of design candidates with the following data:

- Hydrostatic data such as displacement, hull coefficients (Cb, Cp, Cm, Cwp), LCB, KB, etc.
- Resistance curves
- Propulsion motor and battery package specifications
- Weight estimation breakdowns
- Feasibility and optimality assessments
- 3D model of vessel

Fig. 1. Design configurator tool architecture

The following outlines how the tool works. When the user changes or specifies the ranges of main particulars, the tool will search for the design candidates from the database within the given ranges. Resistance data, operating profile, and propulsion efficiency are used to calculate the maximum brake power of the propulsion motor and the total energy required for propulsion between the charging stations. Additional loads, such as manoeuvring (docking, undocking), acceleration, and hotel loads, are added to determine the total net energy capacity of the battery. The gross battery is calculated based on requirements on Depth of Discharge (DoD) % and a margin for End of Life (EoL) capacity. Finally, the maximum weight is estimated by combining the weights of the hull, superstructure, propulsion system, battery, and others. If the displacement of the vessel is larger than the maximum weight, the design is deemed feasible in terms of weight. While the displacement value is relatively accurate since it is calculated from the actual hull geometry, weight estimation may have some uncertainty depending on the assumptions and methods used. Depending on the type of superstructure, equipment, and payload, the maximum weight of the vessel can vary significantly. Users can also adjust the total weight of the vessel to add corrections to the results of the built-in weight estimation method.

Initially developed as a MATLAB standalone application, the tool was later transformed into a web application to enhance user experience and accessibility across platforms. The MATLAB App interface of the tool is shown in Fig. 2, and the Web version of the tool is available at https://tram.myozinaung.com/.

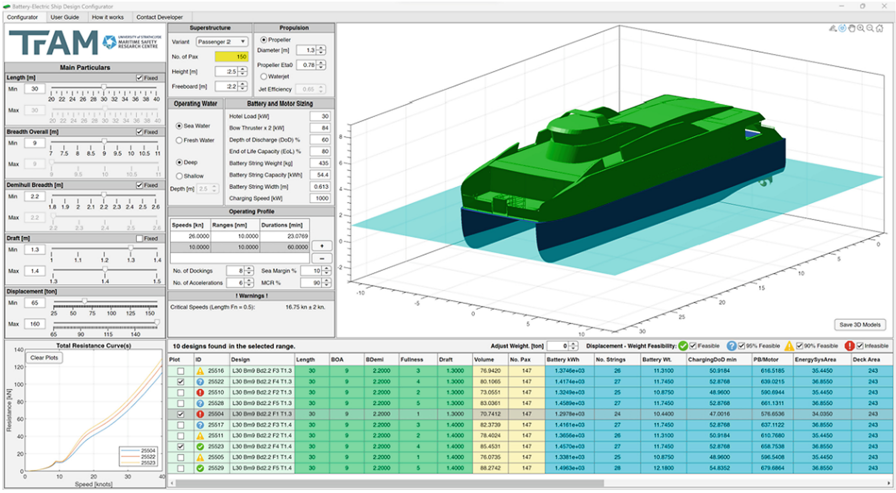

Fig. 2. Battery-Electric Ship Design Configurator Tool (MATLAB App)

3 High-Speed Catamaran Ferry Design Database

This section shows how the design database is generated using the particulars of the demonstrator high-speed catamaran ferry from the EU Horizon TrAM project [9] as a basic design. To generate hull forms of various dimensions and shapes a fully parametric hull model is first developed in CAESES software [10] as shown in Fig. 3. The parametric model is designed to ensure that the hydrodynamic performance of the generated hull is decent for the whole range of design variables.

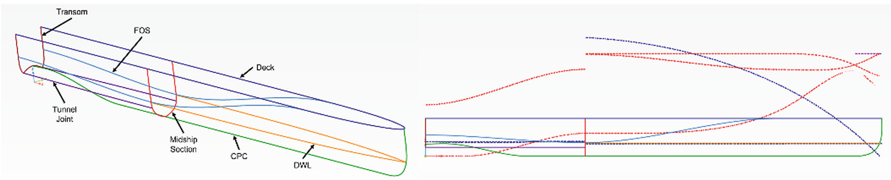

Fig. 3. Parametric Feature Curves and Function Curves (Sectional Area Curve (SAC), Tangent Curves, Section Fullness Curves, Waterline Entrance Angle Curve, etc.)

The four main dimensions used as design variables are length, breadth overall, demi-hull breadth, and draft. An additional parameter called *fullness* is added to create different shapes for the hull with the same dimension. The fullness value of 1 represents the V-shape midship sections while the fullness value of 5 represents the U-shape midship sections. For this particular database, a total of 51030 hull designs are generated, with displacement ranging from approximately 30 m^3 to 150 m^3. The design parameters and their ranges are provided in Table 1.

Each generated design geometry undergoes hydrostatic and hydrodynamic data calculations by connecting the CAESES to the Maxsurf Modeler and Maxsurf Resistance

Table 1. Design variables and ranges for design database generation

Design Parameters	Minimum	Step	Maximum
Length	20 m	1 m	40 m
Breadth Overall	7 m	0.5 m	11 m
Demihull Breadth	1.8 m	0.1 m	2.6 m
Hull Fullness (V or U Shape)	1 (V-shape)	1	5 (U-shape)
Draft	1 m	0.1 m	1.5 m
Displacement	~29 m^3		~151 m^3

[11]. Since the demihulls are slender, Slender Body method [12, 13] with the Molland form factor is used for resistance estimation. It was found that Slender Body method gives relatively accurate results, even though dynamic trim and sinkage are not considered. However, additional corrections are made using high-fidelity CFD and experimental resistance data of the basic hull model. The corrections for shallow water are also done using shallow water CFD resistance simulation results.

For the weight estimations of hull and superstructure, a detailed parametric structural model is first constructed in CAESES as shown in Fig. 4. However, generating variants of the detailed structural model for the whole database is computationally expensive and time-consuming. Therefore, polynomial surrogate models are constructed using only a limited number of structural design variants. Other parts of the weight estimation are derived from the basic design which has the detailed weight estimation data.

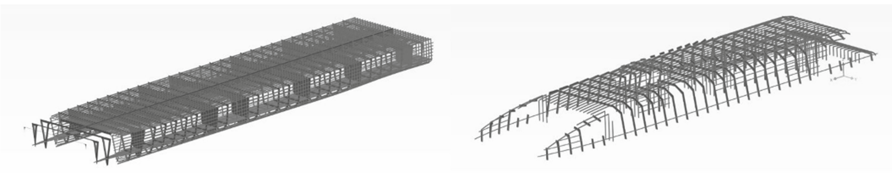

Fig. 4. Parametric Structural Models for Hull and Superstructure Weight Estimation (Source: Authors)

4 Discussion

The developed configurator tool with the catamaran hull database has been tested and verified through feedback from the partners from TrAM project [9], including ship operators, shipyards, and research institutes. The capability of the tool is demonstrated in the designs of two replicator vessels from the TrAM project, one coastal deep water passenger ferry in Belgium and one river bus in shallow London's Thames River [9]. Although the current database is constrained to small catamarans with dimensions given in Table 1, it can be easily extended to other vessel types and sizes by developing additional design databases and suitable weight estimation models. This design automation tool is expected to expedite the transition to zero-emission battery-electric vessels by aiding decision-making processes for ship operators and designers, considering their unique operational requirements. The web version of the tool is available at tram.myozinaung.com [14].

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Unleashing the Potential: Analyzing Modularity Aspects for a 40-Ton Fuel-Cell Powered Long Haul Truck

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Abstract. This abstract presents a concise analysis of the modularity aspects associated with the 40-ton fuel-cell-powered long-haul truck. The objective of this study is to investigate the potential benefits and challenges of modular design in fuel cell-powered heavy-duty vehicles. The integration of fuel cell technology in heavy-duty trucks offers promising potential for decarbonizing the transportation sector and reducing dependence on fossil fuels. However, achieving efficient and cost-effective deployment of fuel cell-powered long-haul trucks require careful consideration of modularity aspects. This study examines the key modularity aspects specific to a 40-ton truck with a full fuel cell-driven propulsion system. The analysis encompasses various components, including the polymer electrolyte membrane (PEM) fuel cell modules, hydrogen storage tanks, and battery system. Outlined high-level requirements, presented challenges, suggested strategies, and envisaged future directions are pinpointed as the principal outputs of this paper, establishing a coherent framework and pragmatic insights for fortifying the modularity and standardization in electric freight transport systems. The discoveries underscore the merits of a modular design in its scalability and adaptability, offering capabilities to modulate the power output of the fuel cell system and the hydrogen storage capacity, thus customizing the truck's performance to adhere to particular operational demands, while also promoting simplified maintenance and component substitution, culminating in reduced downtime and elevated availability.

Keywords: PEM Fuel cell Propulsion · Long Haul Truck · Modularity · Electrification · Sustainability

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1 Introduction

Recently, the emphasis on zero-emission fuel cells in transportation has grown, with expanding applications across various sectors, including cars, trucks, and trains [1]. The heavy-duty truck sector, as this paper's interest, is both energy- and cost-intensive, forcing alternative clean energy solutions to offer range, power, durability, and refueling convenience [2]. Fuel cell electric vehicles (FCEVs) for long-haul trucking offer significant advantages, including fast refueling, reduced infrastructure costs, and lower powertrain weight compared to battery electric vehicles [3]. However, the system cost remains a barrier, with polymer electrolyte membrane fuel cells currently costing around $600/kW, though future technological advancements may reduce this [4]. Despite being in the early stages of development, companies like Nikola are actively pursuing fuel cell-powered trucks, such as the Nikola Tre, aiming for a (500-mile) 800 km range [5]. Toyota and Kenworth have developed the Kenworth T680, with a range exceeding 400 miles (640 km) [6]. Hyundai's XCIENT Fuel Cell Truck, achieves 180 kW output power and a 400 km range with a dual 90 kW fuel cell system [7]. Daimler and Volvo's joint venture, Cellcentric, recently reported that the Mercedes-Benz GenH2 Truck has achieved a 1,000 km range using liquid hydrogen [8]. The reported ranges and power levels have yet to be validated scientifically. Also, comprehensive technical and economic performance analyses remain underexplored.

The technology indicators for Fuel Cell Heavy-Duty Trucks from 2025 to 2035 are summarized in Table 1. This data reflects average values derived from publications by the US Department of Energy, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), and the Strategy Councils of China and Japan [9].

Table 1. Metrics for heavy-duty fuel cell vehicles and hydrogen storage systems [9]

		2025	2035
Heavy-Duty Vehicles	S/kW (System)	195	80
	S/kW (Stack)	115	40
	System Efficiency (%)	65	70
	Stack Durability	22.000	30.000
Hydrogen Storage Tank	Onboard Hydrogen Storage Cost (S/kg)	365	200

The commercialization of fuel cell-powered heavy-duty trucks requires a significant increase in production volumes by 2035, improved system performance, and reduced costs. This challenge is met by advancements in the field, which are expected to boost market penetration gradually. Modular approaches, such as integrating multiple identical-size fuel-cell stacks, can reduce costs by scaling manufacturing and creating various power options. The ESCALATE project showcases how modular designs can lower manufacturing and maintenance costs for fuel cell trucks.

This paper examines the impact of modularity on zero-emission heavy-duty vehicles (z-HDVs), focusing on its benefits for fleet maintenance and its effect on packaging costs.

It highlights how existing modular designs can improve truck production scalability and enhance the performance and feasibility of fuel cell trucks in this sector.

2 Benefits of Modular Design Approach in of z-HDVs

Modularity entails designing key components, like batteries and fuel cells, for easy interchangeability. This approach enhances adaptability, scalability, and simplifies upgrades, resulting in a more cost-effective and sustainable supply chain in the electric vehicle industry [10, 11]. Ulrich [12] outlines the potential benefits of modularity like component economies of scale, product change, product variety, flexibility in use, order lead-time, and decoupling of tasks. However, challenges include static product architecture, performance optimization issues, ease of reverse engineering can occur, increased unit variable costs, and excessive product similarity.

To transition from internal combustion engines to fuel cells for heavy-duty vehicles cost-effectively, the industry often repurposes existing vehicle architectures by integrating fuel cell systems into current engine and storage compartments. The ESCALATE project focuses on improving modularity and standardization to facilitate this shift. Benchmark studies show that modularity offers flexibility in vehicle design and supports converting existing platforms to fuel cell use. Modularity also extends to hydrogen storage, with high-pressure tanks typically placed behind the truck cabin or available spaces across the chassis to optimize space [13].

Modularity provides key advantages for fuel cell-powered trucks: Scalability – easily adjusts fuel cell stacks to accommodate different capacities and road conditions, simplifying design and analysis; Maintenance – enables updates and repairs of balance-of-plant (BoP) components without a full system overhaul, reducing maintenance time and costs; Design Flexibility – optimizes space and weight distribution by allowing varied placement of fuel cells within the chassis, enhancing vehicle performance and efficiency; Power Management – distributes power across multiple fuel cell systems, minimizing converter size and cost, and facilitating cost-effective repairs through module replacement; Control Strategies – supports cooperative and independent control of modules, enabling the development of optimal operating configurations and control algorithms; Customization and Reliability – allows tailored truck configurations and incorporates redundancy, ensuring operation even if a module fails; Packaging – uses a distributed architecture for better space utilization and efficient high-power delivery, balancing between multiple stacks and single stacks based on efficiency and lifespan; and Sustainability – extends the lifespan of fuel cell systems and reduces premature disposal, supporting sustainable heavy-duty vehicles. Table 2 underscores the advantages of using a modular design for fuel cell systems in heavy-duty transportation.

Table 2. Modular design compared to the traditional approach

Scalability	+	Cost effectiveness		Customization	-
Packaging	+	High volume/ Low volume	-/ +	Weight	-
Maintenance	+	Potential points of failure (Stability)	-	Performance	-
Adaptability	+	Component testing	+	Product variety	+

3 ESCALATE Modularization Approach

The ESCALATE project initially focused on modularizing the entire fuel cell system, including the BoP, into 120 kW units. This approach used multiple self-contained fuel cell modules to meet the vehicle's power demands. These modules, defined by specific requirements (as detailed in Table 3), create a flexible and scalable platform, laying the groundwork for future standardization and expansion. The project's modularity requirements ensure seamless integration and scalability, guiding the successful implementation of each module. Through this approach, ESCALATE exemplifies transformative advancements in z-HDVs.

Table 3. Requirements for z-HDV modular design.

ID	Description	Unit	ID	Description	Unit
1	Number of electric-drive units	pcs	7	Minimum energy capacity of single battery pack	kWh
2	Number of fuel-cell stacks	pcs	8	H2 Capacity per tank	kg
3	Minimum power capacity of a single FC unit	kW	9	Minimum power capacity of single battery pack	kW
4	Number of battery packs	pcs	10	Number of DC-DC converters	pcs
5	Number of H2 tanks	pcs	11	H2 Tank diameter	mm
6	H2 Tank length	mm	12	Power per tank	kW

The next phase focuses on expanding and standardizing interfaces, reinforcing the modular approach of the ESCALATE strategy. This involves integrating standardized hydraulic, pneumatic, and electrical interfaces, enhancing adaptability and scalability across various applications. By ensuring seamless integration and interoperability, the ESCALATE project sets a precedent for innovation and technical excellence in electric freight transport, advancing sustainable and efficient mobility solutions.

4 Modularity Aspects of BMC 40-Ton Fuel Cell Truck

Since fuel cell performance and lifespan are influenced by operational modes like cyclic load variations, start-ups, shutdowns, idle and high load operations [14], constant speeds heavy-duty vehicles, are well-suited for fuel cell platforms. However, variable loads during departures or in urban areas can shorten fuel cell lifespan. Therefore, the BMC 40-ton truck design uses modular packs to manage power demands, extending system efficiency and component lifespan through advanced control algorithms.

Commercial vehicle fuel cells typically range from 50 kW to 225 kW. Modular setups facilitate high-power applications. These setups allow for flexible power distribution, potentially enhancing efficiency across various design configurations. A system with multiple fuel cell stacks may outperform traditional setups. For a dual-module system, a controller can direct power according to engine demand, optimizing efficiency. Given these benefits, this study employed two 120 kW fuel cell modules. To achieve an 800 km range without refueling, the study selected four 700-bar hydrogen tanks, each with a 411 L volume, certified under UN ECE R 134, providing 200 km per tank. A 90 kWh battery was also included to power the BoP components during start-up.

A modular power management system requires a corresponding modular thermal management system to maintain optimal fuel cell temperatures. Individual cooling circuits not only boost the BMC truck's efficiency but also offer fault tolerance. If a component fails, the issue is contained, reducing downtime and maintenance costs since only the affected module needs replacement. The truck can still operate at reduced capacity, ensuring deliveries continue with minimal disruption. In addition to balance-of-plant components like air compressors and hydrogen blowers, thermal management components are needed to dissipate heat in fuel cell engines. Cooling circuits and thermal systems can be customized for modularity. Efficient operation requires careful integration of sensors, valves, and actuators with power and thermal management systems. Functional interconnections are designed to ensure seamless truck operation and durability in modular systems. These connections must be robust to endure vibrations, impacts, and heavy loads while improving performance and fuel efficiency. They are divided into electric-electronic and mechanical categories. Electric-electronic connections include DC/DC converters, control hardware, and cabling, while mechanical connections involve thermal circuits and piping. Standard components like connectors and regulators are chosen to balance cost and robustness.

The thermal layout of the system was optimized to achieve the overall vehicle efficiency target. A thermal layout concept of a fuel cell empowered by two identical fuel cell units and a battery system of BMC truck is presented in Fig. 1.

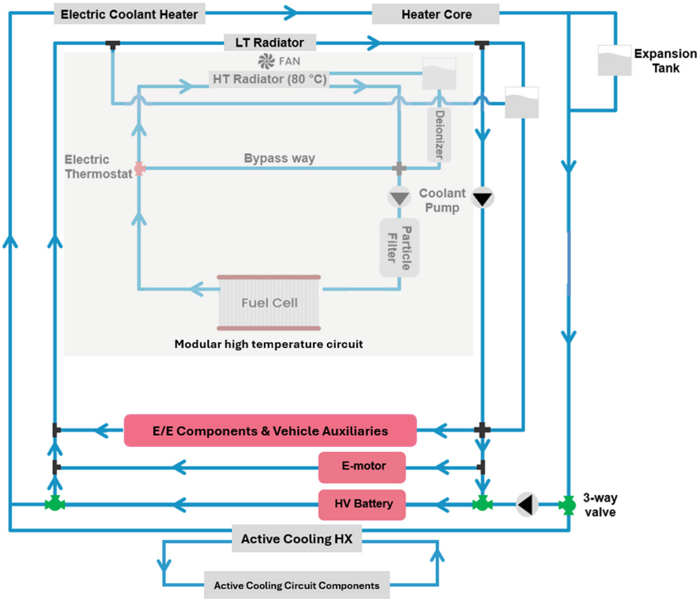

Fig. 1. Proposed thermal layout of a modular 40-ton BMC FC-HDV

The thermal layout divides into high-temperature and low-temperature circuits. Fuel cells use the high-temperature circuit, while other components use the low-temperature circuit. A heating circuit supports battery start-up. These choices highlight the practicality and promise of modular designs for future 40-ton fuel cell trucks.

5 Conclusion

In conclusion, this paper provides insights into the modularity aspects associated with integrating fuel cell technology into a 40-ton truck. It underscores the significance of modularity in enhancing scalability, maintenance, and component interchangeability, ultimately improving the feasibility and performance of fuel cell-powered heavy-duty vehicles. By examining the opportunities and challenges of modular design, this research contributes to the ongoing efforts in advancing sustainable transportation and fostering innovation in the field of electrified road vehicles.

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Real-World Methane Emissions Measured On-Board Two LNG-Fueled Vessels

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Abstract. Real-world studies on-board newbuild vessels powered by modern LNG engines were conducted at several load conditions at-sea and in harbor. Compared to earlier on-board studies, the methane slip variation was suppressed, and lower methane levels could be achieved at lower engine loads as well. Further reduction in methane slip could be achieved with engine piloting a new combustion concept. Measured results could be reproduced with the STEAM Ship Traffic Emission Assessment Model utilizing new parametrization for methane. Studying the normal operation of two LNG vessels (Ro-Pax ferry and a cruise ship) exhibits different engine use profiles of the vessels and may help to identify opportunities to further reduce methane slip by operational choices of the vessels.

Keywords: Methane slip · Shipping · LNG engines · Maritime transport

1 Introduction

The use of liquefied natural gas (LNG) as shipping fuel has increased in recent years and about 20% of the total vessel orders in 2021 were LNG-fueled. Vessels using LNG enable one transition pathway from fossil to non-fossil fuels if LNG from synthetic or biobased origin is utilized. The use of LNG in dual-fuel engines together with liquid fuel for ignition also allows fuel flexibility. Compared to conventional liquid fuels, the use of LNG as marine fuel can reduce the emissions of nitrogen oxides and particulates including black carbon, introducing mainly benefits on air quality and human health. However, the slip of unburned methane, the main component of LNG, to the atmosphere remains a concern. Whereas the higher hydrogen-carbon ratio and energy content of LNG compared to liquid fuels leads to lower emissions of carbon dioxide (CO_2), methane itself is a greenhouse gas (GHG) with a global warming potential of 28–30 times higher than CO_2. The European Union is introducing two regulations that will affect methane emissions from ships: the Emissions Trading System and the FuelEU Maritime, which both include carbon dioxide, methane, and nitrous oxide GHGs.

In the scientific literature, number of values reported for methane slip is limited but shows dependency on engine type and load condition. For 4-stroke low pressure dual fuel (LPDF 4-S) engines, which are the most popular engine type in LNG vessels, the

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literature shows great variation between studies, and significant load dependency, with specific emission values ranging from 1 g/kWh to even 120 g/kWh, highest values being reported at the lowest engine load conditions [1].

2 Methods

2.1 Emission Measurements On-Board

Emission measurements were conducted on-board two state-of-the-art LNG vessels. The first campaign took place in December 2022 on-board a Ro-Pax ferry built in 2021 operating in the Baltic Sea, where two of the ship's engines were studied. The first engine (ME4) was a standard Wärtsilä 31DF, 8-cylinder, 4 400 kW, LPDF 4-S engine build in 2021, whereas the second engine (ME3) was of same size, but it was modified to pilot a new combustion concept. The second campaign was conducted in May 2023 on-board a newbuild (2022) cruise ship operating in the Mediterranean. The engine studied was a Wärtsilä 46DF, 14-cylinder LPDF 4-S engine with output of 16 030 kW.

During both on-board experiments, one measurement point in the exhaust pipe, located a few meters away from the engine, was used for sampling raw exhaust gas. Sampling lines were heated to 180 °C. The speciation of methane was performed using a gas chromatograph (Agilent MicroGC) where a small exhaust sample is injected to a separation column every 3 min and then analyzed. Additionally, methane was measured using Fourier transform infrared spectroscopy (FTIR, DX4000 by Gasmet) where methane is speciated based on its absorbance of infrared light in 20 s resolution.

To calculate emission rates (g/s) and specific emissions (g/kWh), the fuel consumption measured during the steady engine load conditions was provided by the vessel operators, along with the engine load data (power in kW). The vessel operators also provided an LNG bunkering report, which included composition information. A pilot fuel sample was analyzed to incorporate it into the calculation of the exhaust gas mass flow rate using the carbon balance method depicted in the IMO NO_x Technical Code.

2.2 Emission Modelling

A regression model was developed to model the emission rate of methane during the first onboard campaign. Methane emission was measured from both engines with two different measuring devices (GC and FTIR). The two devices yielded similar results and the mean value between the instruments was used for the comparison. Measured concentrations of methane in the exhaust gas (in ppm) were converted to mass unit divided by time (g/s) to match the output of modelled values. Based on the measured values a regression was calculated to find the optimum fit for methane slip as a function of engine load for both engines. These regression formulas were then combined with the STEAM Ship Traffic Emission Assessment Model [2, 3] modelled gas fuel consumption data and compared with the measured values.

3 Results

3.1 Specific Methane Emissions

Figure 1 shows the methane slip emissions observed during the campaign on-board a Ro-Pax ferry (from the two engines ME3, and ME4) together with previous on-board measurements of LPDF 4-S engines reported in the scientific literature.

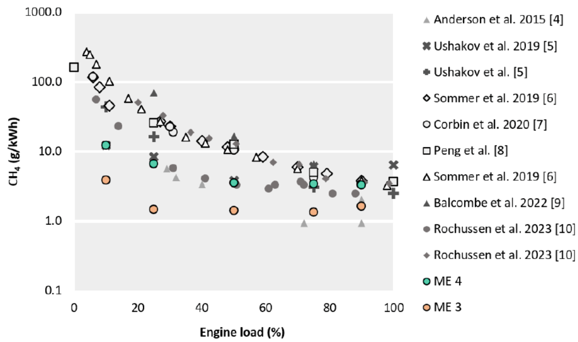

Fig. 1. Methane slip measured on-board a modern diesel-electric Ro-Pax vessel from state-of-the-art engine (ME4) and engine applying a new combustion concept (ME3). Results are compared to other on-board measurements of 4-S LPDF engines [4–10]. Note the logarithmic scale.

The new on-board data highlights that methane emissions from newly constructed engines can be lower than reported in existing literature, particularly when the engines operate at lower loads. Specifically, for the ME4 engine, methane emissions ranged from 3.3 to 3.6 g/kWh at loads between 50–85%, while methane emissions were 7.6 g/kWh at 25% load and 12.4 g/kWh at 10% load. When the engine load exceeded 25%, similar methane emission levels were observed for ME4 compared to a 2016 engine equipped with a new engine calibration [10]. Regarding the ME3, which incorporates a new combustion concept, methane emissions were recorded at 1.4–1.6 g/kWh for loads between 50–85%, 1.5 g/kWh at 25% load, and 3.9 g/kWh at 10% load, indicating that very low methane slip values compared to previous reported values may be reached with the new combustion concept. Earlier, even lower methane emissions of 0.9 g/kWh at 70–90% loads have been reported for a 7.6 MW engine with a larger cylinder [4].

3.2 Comparison with Modelled Methane Slip Values

In its current version, the STEAM models methane slip from a 4-stroke low-pressure otto-cycle dual fuel engine built after 2010 as a constant 3.7% emission of the LNG gas consumption based of the works of [11, 12], which leads to a linear CH4-emission as a function of engine load. Also, based on the findings in [4], STEAM assumes that at loads below 20% the engine only consumes Marine Gas Oil (MGO) that is used as pilot fuel and does not model emissions of methane. From the measured values on-board the Ro-Pax ferry, two findings could be made: Firstly, both engines on board the vessel were using LNG even at loads <20% and secondly, CH4 emission is clearly non-linear as a function of engine load. To develop the modelling, a polynomial regression was fitted to the measured values for both engines:

$$C_{slip} = a * L^2 + b * L + c \quad (1)$$

where Cslip is the methane slip as a fraction of modelled LNG gas consumed, L is the engine load (here from 0–1), a & b are the regression coefficients and c is the intercept. The modeled CH_4 emission for both engines is presented in Fig. 2 and the used regression coefficients, intercepts and statistics are presented in Table 1.

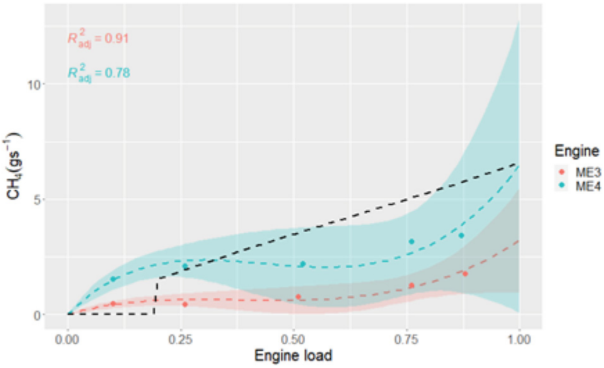

Fig. 2. Measured CH4 emission (g/s) as a function of engine load from two engines (colored points), modelled CH4 emission with STEAM (black dashed line), new modelled CH4 emissions (colored dashed lines) with 95% confidence intervals (colored areas) and goodness of fit (r2).

Table 1. Coefficients (a & b) with their p-values in parentheses, the intercept (c) and its p-value, and adjusted r2 for the polynomial regression of the methane slip for the two engines.

Engine	a	b	c	adj r^2
ME3	0.062787 (0.05)	−0.071024 (0.036)	0.026343 (0.006)	0.747
ME4	0.16153 (0.055)	−0.214497 (0.032)	0.089309 (0.007)	0.945

It can be noticed that the goodness of fit (adjusted r2: 0.91) with the new modelled values is better for ME3 than for the standard engine (ME4, adjusted r2: 0.78). The regression model provides a method to model the methane slip from modern engines as function of engine load, but more measured data from new engines is needed to make definitive conclusions and to finetune modelling parameters for LNG-powered ships.

3.3 Methane Concentrations During Normal Engine Operation

In addition to steady load conditions, methane concentrations of the exhaust were studied during normal engine operation during the first campaign on-board the Ro-Pax ferry

(ME3, Fig. 3). For comparison, methane concentrations during normal engine operation during the second campaign on-board a cruise ship are shown (Fig. 4).

In case of the Ro-Pax ferry, the frequent voyage of appr. 5 h between the two harbors contained relatively more maneuvering operations at low loads and engine load was adjusted more frequently. The Ro-Pax ferry was also equipped with batteries and shore power use, enabling it to run down engines in harbors.

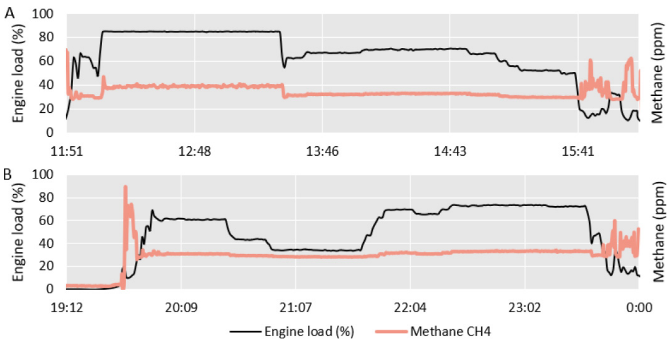

Fig. 3. Methane concentrations measured on-board modern Ro-Pax ferry from engine piloting new combustion concept (ME3) during two voyages Umeå-Vaasa (A) and Vaasa-Umeå (B).

For the cruise ship which operates on a seasonal route between several Mediterranean cities, the engine was operated at high loads of appr. 80% for prolonged periods of several to up to 14 h, with shorter periods of engine usage at 60% at sea and in harbor. Lower load conditions of appr. 20% were utilized during maneuvering during departures and arrivals as well as in the case of ship reducing its speed at sea. For both vessels, the methane concentrations increased at low loads with simultaneously reduced engine power output, meaning that higher specific emissions were produced, similarly to the findings in Fig. 1. The absolute methane concentrations remained lower with the Ro-Pax ferry engine piloting a new combustion concept, but concentrations should not be

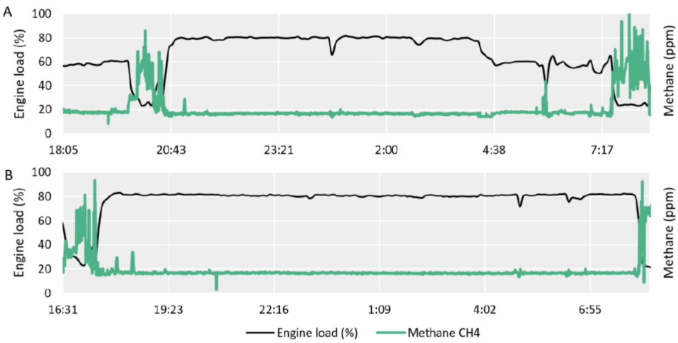

Fig. 4. Methane concentrations measured on-board a newbuild cruise ship. During *v*oyage (A), the ship resided and departed a harbor, sailed at sea overnight and arrived at harbor. During voyage (B), the ship departed harbor, then cruised at sea overnight, until reducing its speed.

compared between the vessels directly due to different exhaust compositions, mass flows, and engine power ratings which specific emission factors account for.

4 Conclusions

Regarding earlier literature, methane slip measured from newbuild engines in this study showed low values. These engines used LNG also at low loads and the share of pilot/gas fuel should therefore be reconsidered when modelling dual-fuel engines and non-linear relationship applied for methane as engine load is reduced. The normal operation measured on-board suggests that in these ships, engines are rarely operated at very low loads but operation at minimum loads of 10–20%, depending on ship type, can occur during maneuvering with increased specific emissions. Reducing low load operation may help to decrease methane slip in addition to engine and aftertreatment development. In future work, comparison of methane slip during steady loads and normal operation, together with refined modelling can improve estimates of methane slip from shipping.

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Electrochemical Processes and Energy Systems Towards Step-Wise Emission Reduction of Marine Transport

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Abstract. The consortium of the NAUTILUS project is developing a pilot marine genset, consisting of a Solid Oxide Fuel Cell (SOFC) coupled with a battery and to be hybridized with the existing LNG fueled Internal Combustion Engine (ICE) generators. The concept enables a step wise scale-up and integration through mild hybridization, balanced hybridization and full replacement of the ICEs. A demonstrator of the genset of 60 kW is being developed which will be validated at DLR. The project is aiming a technology that has the potential to reduce CO2 emissions by at least 40% and particulate emissions by 99% in a vessel meeting the targets of the IMO of 2030. For emission targets beyond 2030, the potential of NAUTILUS genset with synthetic fuels is evaluated. To enable such transition, the reformer unit is conceived to be separated from SOFC power blocks.

Keywords: Emission reduction · Solid Oxide Fuel Cell · Hybrid Genset · LNG · Fuel Flexibility · Synthetic Fuel

1 Introduction

The maritime transport industry contributed with 1.076 billion tonnes to 2.89% of the global anthropogenic greenhouse gas (GHG) emissions, calculated as equivalent CO_2 emissions in 2018 (IMO, 2020). For comparison, the aviation industry, which has been under pressure to cut emissions, contributed with 0.915 billion tonnes to the global GHG emissions in 2019 (ATAG, 2020). In regards to other air pollutants, the latest European environmental assessments show that the international shipping industry contributed with 10% of the SOx, 15% of NOx and 7% of particulate matter (PM2.5) emissions (EEA, 2018). While other transport modes have decreased these emissions, marine transport emissions have continued to rise. If no action is taken, ship CO_2 emissions are projected to increase from about 90% of 2008 emissions in 2018 to 90–130% of 2008 emissions by 2050 for a range of plausible scenarios (IMO, 2020). Therefore, IMO has introduced a strategy in 2018 to reduce carbon intensity of marine transport (IMO, 2018) and envisages to reduce CO_2 emissions per transport work, as an average across international shipping,

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by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008, and that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050 compared to 2008. A further reduction in GHG emissions towards 100% is emphasized, if proven to be possible. A paradigm shift is needed both in on board energy systems and in the marine fuels to reduce the emissions from waterborne transport and to comply with the IMO strategy and regulations of the ECAs. Beside the legislative driver for change, there is public perception. Passenger and cruise ships are in continuous contact with customers and local inhabitants that increasingly demand a measure be implemented for a cleaner environment. EU-project Nautilus is targeting to develop a pilot marine genset system consisting of solid oxide fuel cell (SOFC)-battery hybrid to operate with LNG now to reach IMO emission targets of 2030 and eventually with sustainable fuels to attain targets 2050.

2 Concept of NAUTILUS

Cruise ships marketed currently are powered by electrical energy which is generated using marine diesel fueled internal combustion engine (ICE) generators. The generated power is delivered to a local electric grid via a switchboard which drives the electrical propulsion and supports the hotel load and the ship systems (Fig. 1). The energy demand is met by multiple main generators, typically 4 to 5 with each in the power range of 14–15 MW. Additionally, two redundant diesel generators of 14–15 MW are available on-board, which are allowed to idle, in order to hedge the risks of ship operators and cover the energy needs in case of emergency or failure of the main system. The diesel generators are placed in two engine rooms and an electrical switchboard distributes the electrical power to different loads. Lastly, an additional emergency engine of power range 1–2 MW must be on-board feeding only emergency equipment, which is started if no main engine is running.

NAUTILUS genset is a conceived as a highly efficient and dynamic LNG fueled genset based on a SOFC-battery hybrid system to be coupled with the existing ICE based generators and gradually replacing these ICE generators (Fig. 1).

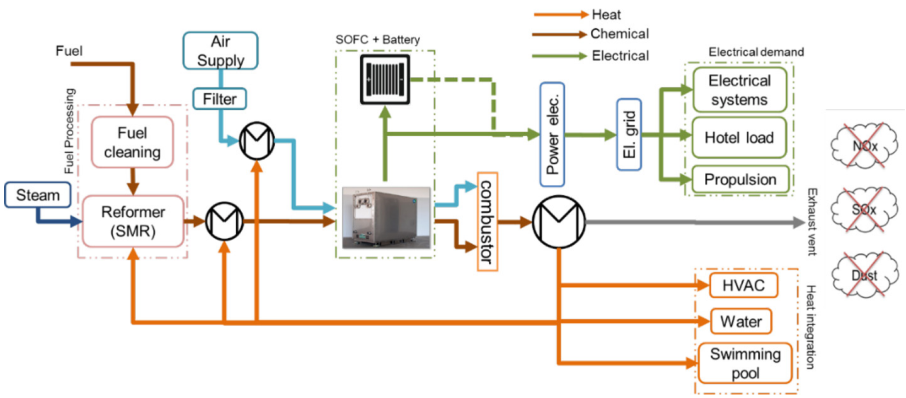

Fig. 1. Proposed SOFC-Battery hybrid electrical power generation system.

SOFCs operate typically above 750 °C with natural gas or reformates of higher hydrocarbons as fuels, using hydrogen as well as carbon monoxide (CO). The SOFCs in the NAUTILUS concept have demonstrated fuel to power efficiencies of 60% and combined heat and power efficiencies of 80%. Not only does it offer higher electrical efficiency compared to other fuel cell technologies, but its higher quality heat can be beneficial for heat recovery, absorption chillers and for purification of water for on-board drinking water supply. Moreover, it does not need an exhaust gas processing unit. Hybridizing this SOFC with batteries in NAUTILUS genset enhances the capabilities to respond to faster transient operation (van Veldhuizen, 2023). As a result, high efficiency can be combined with enhanced dynamic operations and the on-board requirements of power and heat can be catered.

For the integration, a modular approach of the genset to reach MW scales is evaluated. The concept consists of integrating a genset as modular units of 100–500 kWe along with a feasible fuel storage/piping and exhaust gas ventilation without a centralized chimney (Fig. 2). The modular concept enables to make genset integration easier as well as the redundancy factor is increased. With ICE, a modular approach is considered unfeasible due to significantly higher maintenance costs as number of units increase. In the case of SOFCs and Li-ion batteries, the number of units play a minor role in total maintenance cost.

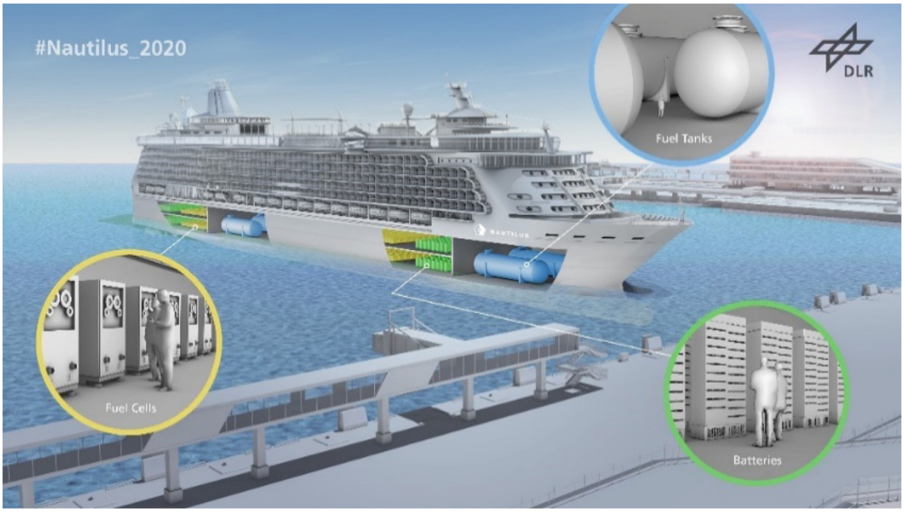

Fig. 2. Schematic drawing that exemplifies the implementation and design of modular NAUTILUS genset.

3 Laboratory Proof of Concept

Laboratory testing represents an important step in the development and implementation of the NAUTILUS demonstrator. The necessary setup and controls were put in place in the test stand GALACTICA at DLR, with the 32 kWe large stack module (LSM) from

SolydEra and 40 kWh Li-ion battery from Corvus, as well as an energy management system (EMS) developed by RWTH Aachen University (Ünlübayir, 2023), in order to follow a transient load demand. The power split is determined by the EMS every instant, and the necessary power is drawn from the fuel cell, with the battery covering the fast transients. In preparation for the experimental campaign, a transient model of the LSM using the in-house developed transient process system simulation framework TEMPEST (Santanam, 2018, Tomberg, 2019, Tomberg, 2022) was developed and validated (Salas Ventura, 2022), and used to carry out pre-simulations of the SOFC & battery genset covering a time-varying ship power profile (Salas Ventura, 2023). One transient experiment is presented in Fig. 3, showing that the genset responds to fast transients in the power demand by combining the ability of the fuel cell to deliver the base load with the battery charging or discharging to complement the demand as necessary. The responses in the air outlet temperature to the transitions in SOFC power are shown in Fig. 3 at the right. Air flow control is implemented to not exceed a specified temperature. Different control strategies developed by RWTH were tested in an experimental campaign, since they lead to varying power splits, as the battery SoC needs to cover the power profiles while remaining within a safety margin. Learnings from the proof of concept experiments are being used to construct a 60 kWe SOFC/Li-ion battery genset demonstrator.

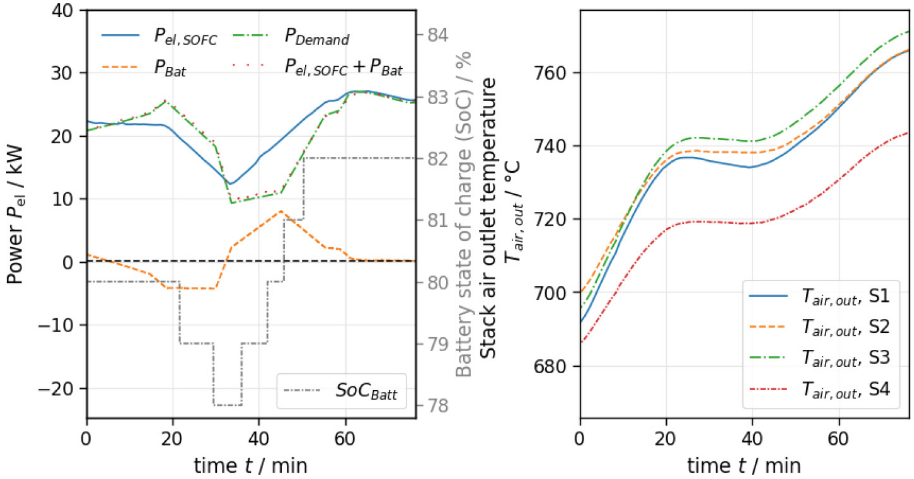

Fig. 3. Experimental results of the laboratory proof of concept at DLR with SolydEra 32 kWe LSM and 40 kWh Li-Ion Battery with implemented hybrid genset control strategy given by EMS developed by RWTH.

4 Beyond 2030 IMO Targets

The NAUTILUS project proposes the following scenario: The LNG infrastructure is fast developing in the ports. LNG availability, deployment and value-chain are well established. Fossil natural gas can be readily blended with synthetic methane from bio sources or from Power-to-Gas. Increasing the blending ratio of sustainable methane into natural gas gradually can allow to reach the IMO targets on net carbon reduction beyond 2030 while utilizing the existing infrastructure and value chain for LNG, and reducing the financial risks for deployment, redundancy and defunct-investments. While supporting this scenario, the NAUTILUS genset is, however, conceived to be able to operate with different future fuels. This will be done by separating SOFC power blocks from the on-board reforming unit. Should a fuel other than liquified methane become the choice, the reforming unit will need to be replaced but remaining genset will not be made de-functional and can continue to operate.

5 Conclusions

The NAUTILUS pilot marine genset, composed of an SOFC-battery hybrid, is under development to be hybridized with the existing ICE generators. This allows a step wise scale-up and on-board integration through mild hybridization, balanced hybridization and full replacement of the ICEs while utilizing LNG. The improved energy efficiency, avoidance of methane slip, and electrochemical conversion is instrumental to reduce CO_2 emissions by at least 40% and particulate emissions by 99% in a vessel meeting the targets of the IMO of 2030. A 32 kWe proof of-concept is currently tested at DLR. First, the transient models are validated, second, the control enhanced for load following purposes using simulation and experiment.

Moreover, a demonstrator of the genset of 60 kWe is under construction which will be validated at DLR. For emission targets beyond 2030, the potential of NAUTILUS genset with synthetic fuels is evaluated. To enable such transition, the reformer unit is conceived to be separated from SOFC power blocks. For future fuels, the NAUTILUS project forwards the idea of blending and displacing natural gas with sustainable methane based on expanding availability of the infrastructure and value chain for LNG, advances in bio-methane and Power-to-Gas technologies and their cost reduction, and avoidance of financial risks linked to the redundancy of technologies or defunct-investments.

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Assessing Electrochemical Energy Storage Technologies for Waterborne Transport Systems

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Abstract. Electrochemical energy storage technologies play a key role in wide adoption of electric waterborne transport systems. Currently, lithium-ion (Li-ion) is the leading battery technology in electric and hybrid maritime applications. However, specific operational requirements such as power peaks and long sailing distances remain a concern with respect to typical Li-ion batteries, mainly due to the limitations in terms of energy and power density as well as safety. While batteries used in most of marine applications are based on established Li-ion technologies, other mature storage technologies such as supercapacitors could be suitable for waterborne applications. Additionally, the next generation battery technologies such as solid-state batteries show promise for addressing some limitations of Li-ion batteries. These alternative technologies have the potential to transform the landscape of electric marine transport systems.

Focusing on waterborne transport systems, this paper provides a review and a comparative analysis of common Li-ion batteries. Additionally, the alternative electrochemical energy storage technologies including supercapacitor and solid-state batteries are investigated and compared to Li-ion batteries. This research provides valuable insights into the advancements and prospects of electrochemical energy storage system for waterborne transport systems.

Keywords: Marine Electrification · Electrochemical Storage System · Supercapacitor · Solid-State Battery

1 Introduction

In recent years, batteries as electrochemical energy storage systems have emerged as an effective solution to address environmental sustainability and operational efficiency challenges within maritime transport sector. The targets related to Greenhous Gas (GHG) emissions set by regulatory agencies such as International Maritime Organizations (IMO) have amplified the significance of battery systems in marine applications. According to the IMO's GHG strategy, the total annual international shipping GHG emissions need to be reduced by at least 70% by 2040 in comparison with 2008 levels [1]. Batteries utilized onboard vessels serve diverse functions, all with the general goal of reducing emissions

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and fuel consumption as well as increasing efficiency and performance. Batteries onboard vessels can be used for electric sailing in full-electric ships engaged in short-distance operations. In hybrid ships, batteries could play multifaceted roles such as peak shaving, load optimization, spinning reserve, boost function, and ramp support [2].

Compared to electric vehicles, maritime transport systems require much larger and more powerful battery storage systems. Moreover, marine transport systems engage in different type of operations with significantly variable operational and environmental conditions [3]. Additionally, maritime batteries are expected to perform for a minimum of 10 years as marine industry standard [3]. As a result, designing battery systems for maritime transport presents unique challenges and considerations.

In this research, after reviewing the maritime battery requirements, a comparative assessment of Li-ion batteries is performed with regards to their weight and cost in marine applications. Furthermore, alternative electrochemical energy storage systems such as solid-state batteries and supercapacitors are evaluated for their suitability in waterborne transport.

2 Application Requirements

The main operational requirements for selection and sizing of batteries for maritime applications are energy, power and number of cycles [4]. Accordingly, it is necessary to determine how much energy is required for each operation, what is the maximum charge and discharge power, and the frequency of cycles the vessel must execute on a daily, weekly, or yearly basis. As per the definition of C-rate which is a unit to measure the speed at which a battery is charged or discharged, the number of cycles and C-rate are the primary requirements for a battery system. In this respect, the selected battery type and size must ensure that it can meet the C-rate and cycle requirements of the vessel for the expected design life. Each battery type has a distinct C-rate and a specific number of cycles it can go through before reaching the end of its lifespan. Typically, the required C-rate and number of cycles for maritime batteries exceed what is feasible for achieving the practical design life of the battery system. Accordingly, as a common approach, the battery needs to be oversized to cope with the application requirements.

3 Comparative Analysis of Li-ion Cells for Marine Applications

In this section, a comparative analysis is conducted between NMC, LFP and LTO battery technologies as the most common Li-ion technologies in marine applications. For this comparison the usable energy for the vessel is assumed to be 1 MWh. The analysis includes a comparison of the weight and cost of cells for each battery type, considering various C-rates and daily cycles. From a plethora of available batteries in the market, three specific cells are chosen, with a particular emphasis on their energy and power density, as well as lifespan. The characteristics of the selected batteries are outlined in Table 1 [5–7].

In this analysis, only cycle aging of the cells is taken into account. The Wohler curves of the different Li-ion batteries given in [8] are adjusted to the cycle life data in Table 1. Figure 1 depicts the cycle life versus depth of discharge (DoD) for the investigated cells.

Table 1. Characteristics of different Li-ion cells.

Cell type	Weight (kg)	Energy density (Wh/kg)	Power density (Continues) (W/kg)	Cycle life	Cost (€/kWh)
NMC	0.88	254	279	1500 (100% DoD)	150
LFP	4.14	186	391	4000 (80% DoD)	130
LTO	0.55	101	533	10000 (80% DoD)	400

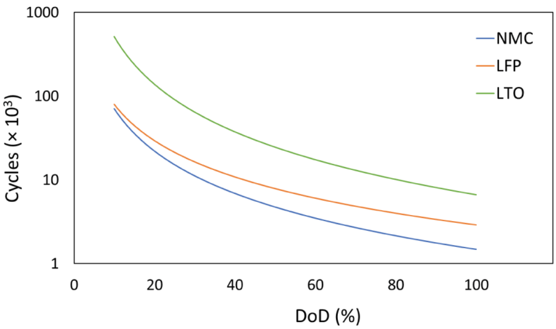

Fig. 1 Cycle life versus DoD.

The analysis deals with finding the minimum installed battery size for 1 MWh usable energy that can meet three criteria:

a) The battery guarantees a 10-year operational lifespan before reaching the end of its useful life.
b) Throughout its design life, the state of charge (SoC) of the battery stays within the range of 10% to 90%.
c) The battery delivers the maximum required power as dictated by its power density.

Figure 2 shows the heat map corresponding to the weight of the cells. Regardless of cycle numbers, NMC is unfavorable at C-rates over 4C, with LTO exhibiting the best performance and LFP falling in between. This is attributed to the high impact of power density of the cells on the required installed battery size. At low C-rates and high cycle numbers, LTO exhibits the lightest weight thanks to its exceptional longevity features. Conversely, at low cycle numbers, LFP and NMC surpass LTO since they require less oversizing owing to degradation. For cycles less than 1 and C-rates below1.5C, NMC emerges as the optimal solution due to its superior energy density.

Figure 3 shows the heat map representation for the cost of the cells at different C-rates and cycles. As it is seen, LFP gives the best cost at all conditions. However, at C-rate and cycles both less than 1, there is a slight difference between LFP and NMC.

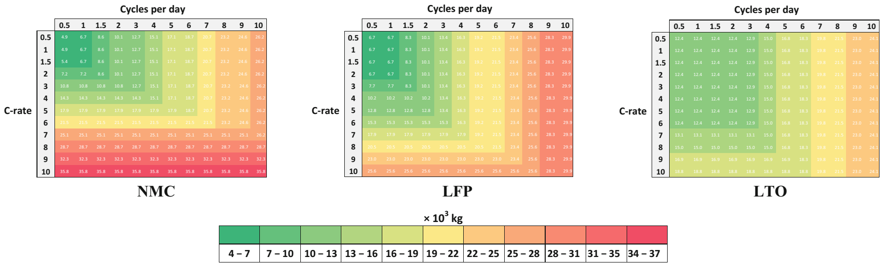

Fig. 2 Heat map corresponding to the weight of the cells. [Source: Authors]

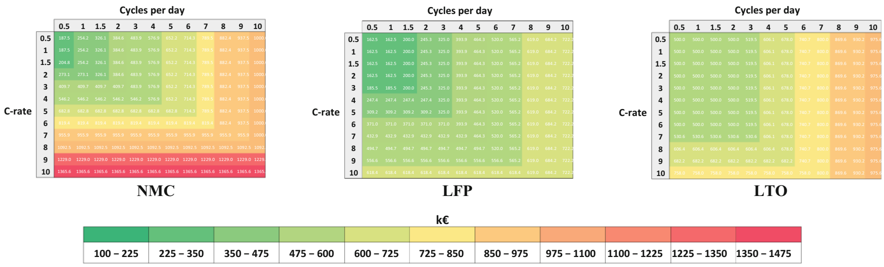

Fig. 3 Heat map corresponding to the cost of the cells. [Source: Authors]

4 Solid-State Battery

Solid-state battery (SSB) is a type of battery technology employing a solid electrolyte rather than the liquid electrolyte used in conventional Li-ion batteries. This distinctive construction offers several advantages, including higher energy density and enhanced safety. These benefits make solid-state batteries an attractive energy storage for powering electric ships, augmenting both cargo capacity and the sailing distance thanks to its high energy density. Compared to traditional Li-ion batteries, SSBs are far less prone to encountering thermal runaway, thanks to their lack of flammable liquid electrolytes. This safety attribute is highly important for ships operating in harsh marine environments with limited options for emergency evacuations.

There are three primary categories of solid-state batteries: semi solid-state, quasi solid-state and all solid-state batteries. The use of SSBs in electric ships and electric vehicles is currently in its early stages as the technology is still undergoing research and development. To gain an understanding of SSBs against traditional Li-ion technologies, a semi SSB (SSSB) with characteristics given in Table 2 is examined in contrast to NMC and LFP batteries. It is worth noting that the cell cost is omitted as a factor in this comparison, as technology is not available yet at economies of scale. Due to lower cycle life and power density compared to Li-ion, only applications characterized by low cycle number (less than 100 cycles per year) and low C-rates (below 0.4 C) are considered. This range specifies vessels with a relative long range like cargo vessels, cruise ships, inland barges, and so on.

Table 2. Specifications of semi solid-state battery (SSSB).

Shape	Weight (kg)	Energy density (Wh/kg)	Power density (Continuous) (W/kg)	Cycle life
Pouch	1.08	350	150	1000 (80% DoD)

As it is seen in Fig. 4, the C-rates in the range of 0.1 to 0.4 don't have any impact on the cell weight. With respect to cycle number, for cycles below 50 cycles per year, the weight of SSB cells is 38% and 88% lower than NMC and LFP cells, respectively. As the number of cycles increases, this difference tends to decrease mainly due to the lower cycle life of semi SSB.

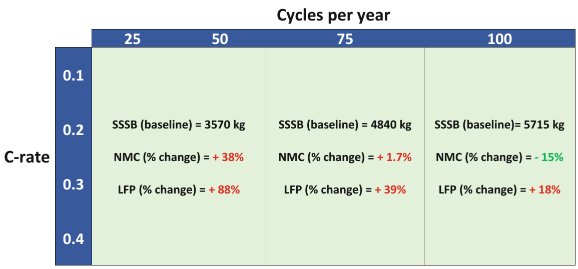

Fig. 4 Comparison of the cell weight for vessel with 1MWh usable energy.

5 Supercapacitor

Supercapacitors (SCs) are defined as a type of devices that store and release electrochemical energy with the process of reversible adsorption and desorption of ions at interfaces between electrolytes and electrode materials. Compared to Li-ion batteries, SCs have a long cycle life (a few hundred thousand cycles), very high power density (a few thousand kW), and are considered a very safe technology, exhibiting excellent performance across a wide range of temperatures. SC technology is mature in comparison to Li-ion and solid-state batteries, having been in existence for many years. However, the main drawback of SC is very low energy density which is typically below 10 Wh/kg.

With respect to electric and hybrid marine applications, thanks to the high power density of SCs, a properly sized SC could contribute to shaving high peak powers and avoid oversizing battery system. Moreover, this reduces the stress on batteries and improves the cycle life of the battery system. Using supercapacitor in marine and port cranes could be another interesting application as the kinetic energy of the loads moved could be partially recovered in an electrical storage. Figure 5 compares the energy and power density of a suitable SC for marine applications against Li-ion and SSSB investigated in this research.

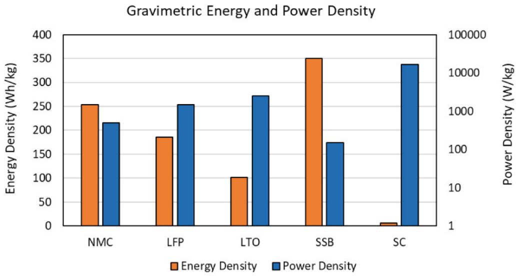

Fig. 5 Comparison of energy and power density of SC and battery technologies.

6 Conclusions

In this work, a comparison is made between the common Li-ion batteries and emerging semi solid-state batteries for marine applications. The results show that choosing the appropriate technology involves a trade-off between size and cost, necessitating an evaluation of various technologies to determine the most suitable cell technology. Semi solid-state batteries can significantly reduce the size of the battery system for high energy applications. It is important to note that this paper has been focused on cell level analysis, while due to the higher safety of solid-state battery and supercapacitor, most improvements of employing such technologies can be made through differences in system design compared to Li-ion batteries. The comparison of such technologies at system level will be the topic of our future research.

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A Short Review of Ammonia Compression Ignition Engines for an SOFC-ICE Power Plant for Shipping

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Abstract. Ammonia is considered one of the most promising hydrogen and energy carriers for decarbonizing deep-sea shipping and other remote heavy-duty applications. The AmmoniaDrive power plant concept uniquely combines Solid-Oxide Fuel Cell (SOFC) and Internal Combustion Engine (ICE) technology to address the issue of how to convert e-ammonia, produced from renewable resources, into useful on-board power safely and effectively, without the need for fossil fuels as combustion promotor. This paper introduces the AmmoniaDrive concept, outlines the challenging combustion properties of ammonia and ammonia-hydrogen mixtures and provides a short review of Compression Ignition ICE research for ammonia-fuelled engines. Three promising combustion concepts are introduced to give direction to further numerical and experimental research.

Keywords: Ammonia · Hydrogen · reciprocating Internal Combustion Engines · Compression Ignition · on-board Power · Propulsion and Energy Systems

1 Introduction

In the fast approaching hydrogen economy, many researchers and engineering professionals consider ammonia (NH_3) as a promising hydrogen (H_2) and energy carrier to decarbonize hard-to-electrify economic sectors. In deep-sea shipping and other remote heavy-duty applications, ammonia may be applied directly as a fuel in reciprocating Internal Combustion Engines (ICEs) combined with a promotor fuel. Several research initiatives therefore investigate and develop ammonia ICE technology ([1–4]). The promotor fuel in many research initiatives is a hydrocarbon fuel originating from crude oil, i.e. a fossil fuel. The next challenge is an ammonia-fuelled power plant concept that does not require fossil fuel. A novel concept is introduced here, which uniquely combines Solid-Oxide Fuel Cell (SOFC) and reciprocating ICE technology in a single-fuel, highly efficient power plant for ships and other heavy-duty applications. We refer to this concept as the AmmoniaDrive power plant.

The power plant concept utilizes ammonia as both hydrogen and energy carrier and is expected to have a relatively small, and thus acceptable, impact on the ship design.

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When the ammonia is produced from renewable resources, i.e. "green" ammonia or e-ammonia, the energy chain is zero-carbon.

1.1 AmmoniaDrive Power Plant Concept

The AmmoniaDrive power plant makes optimal use of the strengths of both energy converters (SOFC & ICE). Figure 1 depicts a schematic overview of the AmmoniaDrive power plant concept. The SOFC produces electric power and is fuelled by ammonia. The ICE produces mechanical power and is fuelled by ammonia and hydrogen. The hydrogen originates from the hydrogen-rich anode off gas of the SOFC. The hydrogen is used as a promotor fuel in the ICE, in theory without any hydrocarbon (fossil) fuel.

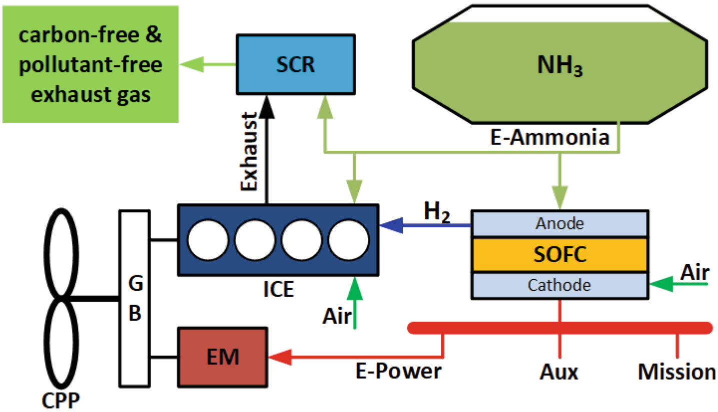

Fig. 1. The AmmoniaDrive SOFC-ICE on-board power plant concept.

The components in the AmmoniaDrive power plant concept are not yet commercially available, especially not at the industrial scale relevant for maritime applications. This also holds for the NH_3-H_2 ICE, whose fundamental working principles are influenced by technical details of the engine and the challenging combustion properties of ammonia. Further research into injection strategies, ignition mechanisms, and resulting combustion modes will be performed to better understand the principles and overcome the challenging combustion properties of ammonia.

As part of this research, the literature on Compression Ignition (CI) ICEs partly fuelled by ammonia has been collected and analyzed to identify knowledge gaps and research opportunities. The study [5] identified advanced CI combustion concepts like Reactivity Controlled Compression ignition (RCCI), Premixed Charge Compression ignition (PCCI), and Partially Premixed CI (PPCI) as potential candidates for operating NH_3-H_2 CI engines, Sects. 2 and 3 comprehensively provide the main results of this literature study. Section 4 discusses the three promising concepts mentioned above and provides an outlook to the experimental research that will be performed to enable the further development of the AmmoniaDrive concept.

2 Fuel Storage and Combustion Properties

The properties of ammonia and hydrogen differ from those of diesel-like fuels. This will have an impact on the ICE and on the fuel-related common practices in the heavy transport industry. An overview of the fuel properties is given in Table 1.

Table 1. Several properties of NH_3, H_2, and diesel ([1] [6], [2] [7], [3] [8], [4] [9])

Property	Unit	Ammonia	Hydrogen	Diesel
Storage method	–	Compr liquid[1]	Compr liquid/gas[1]	Liquid[1]
Storage pressure	MPa	1.03[1]	0.1/24.8[1]	0.1[1]
Storage temperature	K	298[1]	20/298[1]	298[1]
Energy density	MJ/m^3	11300[1]	8539[1]/2101[1]	36403[1,2]
Autoignition temperature	K	924[1]	884[1]	503[1]
Stoichiometric air/fuel ratio	–	6.05[3]	34.33[3]	14.5[2]–17.4[3]
Lower Heating Value	MJ/kg	18.5[2]	120[2]	42.5[2]
Latent heat of vaporization	kJ/kg	1370[2]	445.6[2]/-[2]	270[2]
Laminar burning velocity at $\varphi = 1$	m/s	0.07[4]	3.51[4]	0.86[4]

Storage-wise the large difference in energy density is of importance, especially for long-range / heavy-duty applications. With regard to combustion properties, note the large difference in the lower heating value (LHV), which has a direct relationship with the amount of fuel needed.

Another notable difference from diesel fuels is the high latent heat of vaporization of ammonia. This causes a large cooling effect where the fuel evaporates. This partly explains the lower NO_x emissions than often expected when using a nitrogen-based fuel. It may also result in a requirement to heat the ammonia supply in some experimental set-ups. Another important property for engines is the corrosivity of ammonia. Ammonia is corrosive to copper (alloys), nickels and plastics. This is important for the design of the ammonia supply system.

Ammonia is used in combination with other (promotor) fuels, because pure ammonia has unfavorable combustion properties in typical ICE conditions. Understanding the fuel mixture composition is essential to compare and interpret the results of experimental studies, as those in Sect. 3. The compositions are often defined by either energy percent ($\%_e$), volume percent ($\%_v$), or mass percent ($\%_m$), e.g. an ammonia/hydrogen mixture at 323K and 1 bar of 80/20$\%_v$ NH_3/H_2 equals 82/18$\%_e$ and 95/5$\%_m$ NH_3/H_2.

3 State-of-the-Art NH_3-Fuelled CI ICEs Experimental Results

Conventional dual-fuel (CDF) engines, which are now being developed by marine engine OEMs, can achieve up to 40–60%$_e$ ammonia when it is combined with diesel. In these CDF engines, the ammonia is commonly injected in the inlet ports or directly at low pressure and the diesel is directly injected at high pressure when the piston is close to Top Dead Centre (TDC). Advanced compression ignition concepts are required to achieve higher ammonia energy fractions. Experimental research results of higher ammonia fractions using CI combustion is limited and this is even more so for the combination of ammonia and hydrogen. Promising experimental results have been achieved with homogeneous charge compression ignition (HCCI) in [10] and reactivity controlled compression ignition (RCCI) in [11].

The HCCI combustion concept was fuelled by an ammonia-hydrogen mixture and achieved up to 94%$_v$ ammonia in [10]. However, it required an inlet temperature of 240°C and a compression ratio of 22. The limiting factor of this concept was the pressure rise rate.

The RCCI concept was fuelled by an ammonia-diesel mixture and achieved up to 81%$_v$ of ammonia in [11]. However, it still required 19%$_v$ diesel. The limiting factor of this experimental set-up was the limitation of their turbocharger.

Based on the experimental engine results, five objectives are identified to improve the feasibility of CI combustion of ammonia. These are:

1. To lower the required compression ratio w.r.t. the CR of 22 required for the HCCI combustion concept.
2. To lower the intake temperature w.r.t. the required inlet temperature for the HCCI combustion concept.
3. To reduce the pressure rise rate compared to the HCCI concept
4. To reduce the amount of carbon-based fuel compared to the RCCI concept.
5. Minimizing the formation of pollutants

In order to minimize the required amount of carbon-based fuel, the choice of fuel is also relevant. Hernandez et al. [12] has investigated the autoignition of mixtures of sustainable hydrogen carriers and carbon-based fuels. Their results show that Hydrotreated Vegetable Oil (HVO) has better results with ammonia than (bio)diesel.

4 Promising NH_3-H_2 CI Combustion Concepts

Three CI combustion concepts have been created by combining the identified objectives mentioned above, available literature and the possibilities created by the AmmoniaDrive concept. The three concepts are shown in Fig. 2.

Concept 1, the RCCI concept, is based on controlling the reactivity by changing the mixture composition of ammonia, hydrogen, air, and HVO. There are two modifications compared to the RCCI combustion concept of Chiera et al. [11], the addition of hydrogen and replacing diesel by HVO. Both modifications are aimed at minimizing the required amount of carbon-based fuel by improving the combustion of ammonia. Hydrogen has been shown to be a combustion accelerant for ammonia [13].

Concept 2, the PCCI stratification concept, is based on controlling the combustion by varying the stratification in the combustion chamber. The stratification is intended to decrease the pressure rise rate. Achieving the desired in-cylinder stratification and adapting it to operational conditions, would require a sophisticated injection system.

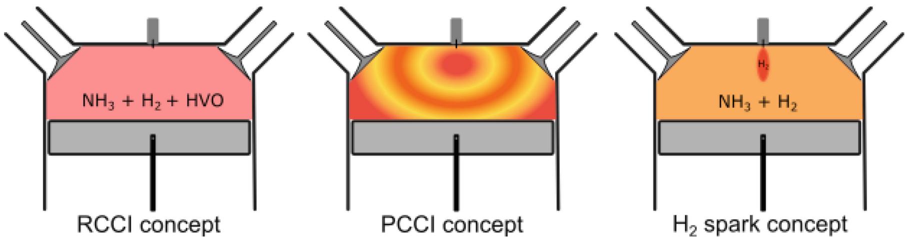

Fig. 2. Three combustion concepts for CI combustion of ammonia and hydrogen.

Concept 3, the hydrogen spark concept, is a combination of a homogeneous charge and dual hydrogen injection and may be regarded as a PPCI concept. The ammonia and early hydrogen injection form a homogeneous mixture leading to a higher flame speed of the mixture compared to pure ammonia operation. The second hydrogen injection causes a local hydrogen-rich region. This region should auto-ignite resulting in two options; 1) a propagating flame ignites the homogeneous NH_3-H_2 mixture, 2) an increase in cylinder temperature, due to the combustion of the second hydrogen injection, causes the homogeneous NH_3-H_2 mixture to auto-ignite.

These advanced compression ignition combustion concepts and/or combinations of them will be investigated to improve the feasibility of ammonia as a CI ICE fuel.

5 Conclusions

The growing interest in ammonia as a maritime fuel is promising and underlines the need for research and development of ammonia-fuelled shipboard power plants to prepare for the fast-approaching hydrogen economy. The AmmoniaDrive project is looking to eliminate fossil-fuel dependency and corresponding harmful emissions altogether by utilizing an innovative SOFC-ICE combined cycle. One of the objectives of this project is to improve the feasibility of ammonia as an ICE fuel. To do so, the maximum attainable ammonia energy fraction has to be increased, compared to available experimental engine results, whilst staying within engine limits, emission requirements, and maintaining good engine performance. More research towards advanced combustion mechanisms utilising the Compression Ignition principle is required to achieve this.

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Green Mobility for Small-Medium Size Ports: A GHG Emissions Web Calculator

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Abstract. Small and medium-sized ports are important hubs in logistics chains and support 90% of the world's seaborne trade. It is therefore crucial to achieve the decarbonization targets set by the European Union through the European Green Deal, as well as other EU transport policy objectives.

The main objective of this work is to develop a web calculator of greenhouse gas (GHG) emissions related with the different transport modes to/from/in the ports of Aveiro and Figueira da Foz, located in the Centre region of Portugal. The calculator will follow the EMEP/EEA emissions calculation methodology, which is based on the energy consumption of transport and relates it to vehicle and fuel emission factors, thus providing reliable values for the GHG emissions released by vehicles during port operations. The calculator will be integrated into the website of the Port Administrations of these ports to be easily accessible to different types of users and to raise awareness of the consequences of the logistics and operational processes that take place in these ports.

Keywords: Green Port · Greenhouse Gas Emissions · Web calculator

1 Introduction

The movement of goods is essential for the modern global economy. However, this essential function comes at a significant environmental cost, as the transport sector is a major contributor to greenhouse gases (GHG) emissions. Among the different modes of transport, maritime transport is highlighted as it accounts for more than 80% of the world's trade in goods [1]. These ports serve as crucial connectors between maritime and land-based transport modes, ensuring the efficient distribution of goods and reducing road congestion. However, these activities also contribute to GHG emissions, making it essential to address the emissions associated with these ports to achieve decarbonization goals. The transport sector itself, including port-related activities, accounts for nearly 25% of all GHG emissions in Europe [2]. Achieving the decarbonization targets outlined in the European Green Deal and other EU transport policy objectives is imperative to effectively tackle climate change.

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As a result of the innovation and ambition of Port of Aveiro, despite being a small and medium port, in 2019 was considered the national port with the highest growth, which shows its potential. Being aware of the need to develop the energy transition and decarbonization specific targets, the Port Authority had started to implement some measures, but a more comprehensive plan involving all the port community had to be addressed to achieve this goal. So, small and medium-sized ports have unique challenges themselves, setting the stage for the need for a GHG emissions calculator.

This paper presents a comprehensive GHG emissions calculator capable of assessing GHG emissions across a spectrum of transport modes to, from, and within the small-medium ports of Aveiro and Figueira da Foz, located in the Centre region of Portugal. It places particular emphasis on the unique challenges faced by small and medium-sized ports in terms of emissions and sustainability. This calculator is in line with these goals, offering a solution to quantify and reduce emissions associated with the transport of goods to, from, and within these ports. The specific objectives of this work are:

1. To promote sustainable choices and to provide information to the users of the ports regarding the optimal and most eco-friendly vehicle and fuel options available to use. This approach encourages individuals and businesses to make environmentally responsible transport choices. To achieve this, the GHG emissions calculator incorporates data on a wide range of fuel options available on the market, including their production pathways, to empower users with the knowledge they needed to choose the most sustainable and environmentally friendly alternatives.

2. To raise environmental awareness: a key objective is to raise awareness of the environmental impact of the logistics and operational processes that take place in these ports. By doing so, this work aims to inspire and encourage environmentally conscious practices among stakeholders and port users. The calculator not only quantifies emissions, but also provides insight into the environmental impact of different fuel and transport choices, thereby fostering a greater understanding of the need for sustainable practices in port operations.

This work is part of the project "A-AAGORA - Blueprint for Atlantic-Arctic Agora on cross-sectoral cooperation for restoration of marine and coastal ecosystems and increased climate resilience through transformative innovation" funded by Horizon Europe, whose main objective is to restore the marine ecosystems and increase climate resilience in the Arctic and Atlantic basin. By addressing these objectives, the project strives to contribute to the reduction of GHG emissions associated with port operations and to promote sustainability within the transport sector while simultaneously enhancing the Social Readiness Level (SRL) by empowering users with information and raising awareness of eco-friendly options.

2 Calculator Architecture

To create a calculator that accurately represents the CO_2 emissions from mobility to/from/in the Port of Aveiro and Port of Figueira da Foz, an architecture was developed that divides the analysis of transport according to complexity (Fig. 1). Three levels of analysis have been created where the complexity of the data required for the calculation increases in parallel. However, any user will have access to all levels of analysis and this division was made to make the use of this tool as comprehensive as possible.

The first level is designed to assess a vehicle, piece of equipment, or vessel individually. This level includes passenger cars, light cargo vehicles, heavy cargo vehicles, trains, ships, and any type of port cargo handling equipment. It will be the simplest to perform and will require the minimum amount of user input, as the analysis is intended for use by a citizen or port worker.

The second level calculates the emissions of a fleet performing a stage of the logistics chain for a commodity. At this level, only cargo vehicles and equipment are counted, as this level of analysis is aimed at transport companies and entities with a physical presence in the ports. Tier 3 is used for all modes of transport, whereas at the first level, Tier 2 was defined for road and rail transport to simplify the use of this calculation tool.

The third level is the most comprehensive of all and aims to simulate a complete logistics chain. It is possible to add all types of vehicles, equipment, and ships to quantify CO_2 emissions during the transport of a commodity. The results can be saved, compared, and exported to Excel. This level is intended for logistics companies and port authorities.

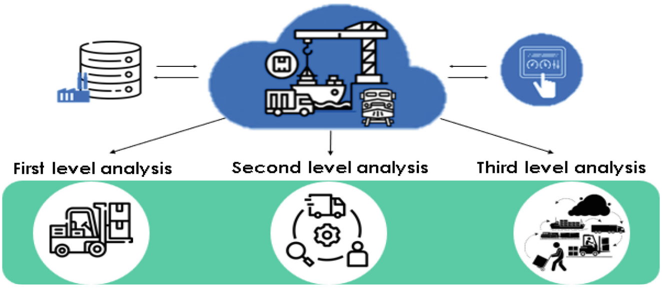

Fig. 1. Schematics of the calculator's architecture

To further assist the correct use of the tool, an information section was created with the description of the levels and some recommendations for the inputs. Finally, and to complement the development of the tool, users are asked to answer a short survey of 3 questions after using the calculator. This will serve to assess the Societal Readiness Level (SRL) of the web calculator to perceive the real extent to which this tool will be integrated into everyday society and port community needs.

3 Calculation of GHG Emissions

In this section, we will explore the methods and methodologies employed to quantify GHG emissions, with a particular focus on the direct CO_2 emissions associated with the different modes of transport within ports. The methodology chosen is EMEP/EEA emission inventory, developed by the European Environment Agency [3], and has successive updates according with the European transport and environmental policies.

It was necessary to collect the emission coefficients of the most common types of fuel, and the alternatives available on the market, with special attention to biofuels and their blends, electricity, ammonia, methanol, and hydrogen. Ammonia and methanol were only considered for ships. The ones that are powered by methanol use a mixture of methanol and marine diesel. The same applies to ships using ammonia [4].

Emissions factors for biofuel blends are calculated using the fossil emission reduction values provided by the Renewable Energy Directive II (RED II) [5] and considering that biodiesel is produced from used cooking oil and that ethanol is produced from maize straw. To quantify the CO_2 emissions from electric or plug-in hybrid vehicles, the CO_2 emission factor related with the electricity production (g/kWh) in Portugal in 2021 was considered [6]. Indirect CO_2 emissions regarding the electricity or hydrogen consumption were not considered.

The maritime mode encompasses the operational aspects of ships and vessels, with the latter category encompassing pilot boats, tugboats, and fishing vessels. Pilot boats serve the vital function of transporting on-duty pilots within the port, facilitating their boarding and disembarkation from ships to facilitate port maneuvers. Tugboats, on the other hand, play a crucial role in assisting ships during their entry and exit from the port, aiding in navigation and facilitating ship docking procedures.

To quantify CO_2 emissions resulting from maritime activities in both ports, we employed Tier 2 and 3 [3]. At the third level the user has the possibility of providing the direct fuel consumption of each ship. For the sake of variable substitution, emission factors specific to CO_2 for each fuel were sourced from EMERGE dataset [4]. Nowadays,ships powered by methanol use a mixture of methanol and marine diesel. This is also true for ships powered by ammonia. It is important to note that in ammonia propulsion systems, the source of CO_2 is the portion of marine diesel [7]. For systems where the energy source is green hydrogen, it is considered that the fuel cells have an efficiency of 53.8% [7].

The road mode encompasses activities associated with passenger cars, light commercial vehicles, and heavy commercial vehicles. Users may input details on vehicle classification, fuel type, travel distance, and load. The tool accommodates a variety of fuels including gasoline, diesel, compressed natural gas (CNG), liquified petroleum gas (LPG), and electricity, allowing accurate evaluations according to different types of automobiles. To achieve a user-friendly calculator the Tier 2 was used in the first level of the tool, in which the fuel consumption used was the typical value provided by the methodology [3].

The rail mode encompasses locomotive operations facilitating the movement of wagons. The quantification of CO_2 emissions from train activities was grounded in Tier 2 [3], which combines the hours of activity, the output power, the number of locomotives, the load factor, and the emission factor of the fuel. Due to operational constraints, it is worth noting that the port terminals do not incorporate power line within their premises, necessitating the use of shunting locomotives for all handling involving electric locomotive wagons. To evaluate different railway configurations for their environmental impact, diesel engines can be compared to those using biodiesel or electricity which are all considered viable fuel options.

Non-road cargo handling equipment are elements that allow cargo handling operations to be carried out. The quantification of CO_2 emissions was based on Tier 3. A comprehensive approach for assessing different types of handling equipment and fuels like electricity, LPG, diesel, B15 and B100 provides an efficient method for accurately calculating their respective contributions towards overall emission levels.

4 Conclusions

This work aimed to present the development of a CO_2 calculator. This open access tool based on scientifically supported calculations will be integrated in the websites of the Ports of Aveiro and Figueira da Foz, which means that citizens, workers from transport and logistics companies as well as the Port Authority decision makers can take advantage of it. It will contribute to raise awareness among different port actors towards the ultimate objective of carbon neutrality in ports. In fact, this tool can be used by actors of any Atlantic port environment. The calculation methodology can be simplified or more complex, from a single piece of equipment to the logistics chain, with the possibility of combining different fuels, means of transport. Upon the input of the relevant parameters, the calculator delivers of CO_2 emissions estimates for each mode of transportation. These results empower stakeholders to make informed decisions regarding route optimization, fuel choices, and equipment upgrades, ultimately contributing to emissions reduction. The possibility of combining and comparing different "what-if" scenarios was tested.

In conclusion, the web calculator presented here is an user-friendly tool for assessing emissions from multimodal freight transportation. By aiding in the quantification of emissions, this calculator supports environmentally responsible decision-making in the freight transportation sector, contributing to global decarbonization efforts. For future work, the authors would like to apply this tool to other ports in the country and even outside Portugal, since the calculator was developed to have easy scalability.

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Retrofit Solutions to Reduce GHG Emissions in Maritime Transport

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Abstract. In this paper, the energy-saving and green solutions developed within the RETROFIT55 EU project are presented. The combination of technologies elaborated depends on the operational scenario of the retrofitted ship, the highest gains in fuel oil consumption, and the reduction of harmful life cycle emissions. Two innovative solutions namely Wind Assisted Ship Propulsion (WASP), Air Lubrication System (ALS), as well as mature technologies, such as operational optimization, smart energy management of electrical systems, and hydrodynamics-based design optimization, are developed and integrated. The project aims at setting up a web-based platform through which the user can browse a catalogue and combine different retrofitting options. Each option is described in terms of surrogate models which allow to compare the different configurations in terms of specific key performance indicators.

Keywords: Green Ships. Design for Retrofitting · Decarbonization · Marine Technologies

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1 Introduction

The research project RETROFIT55 aims to develop decarbonization solutions and green technologies which can be used by shipyards and shipowners when retrofitting a ship to reduce fuel consumption and Green House Gas (GHG) emissions. The project focuses on solutions to improve the ship efficiency (e.g. ALS, Smart Energy Management systems, holistic Hydrodynamic and Operational optimization, etc.) as well as solutions to exploit renewables or zero- and low-emission energy sources (e.g. WASP). Retrofitting new solutions into an existing ship is more complex than developing a new design. This is because of the need to balance retrofitting options against operational constraints and existing ship arrangements. The new solutions should comply with the regulatory framework, be cost effective and ensure sustainability from a life-cycle perspective. The project aims to assist ship owners and shipyards in selecting a retrofitting strategy via the application of an AI based Decision Support System (DSS). The DSS is supported by surrogate models demonstrated during the project.

Section 2 outlines the different technologies developed, Sect. 3 is devoted to the presentation of the web-based catalogue. Conclusions are drawn in Sect. 4.

2 Innovative Technologies

2.1 Passive Air Lubrication System - PALS

The frictional component of hull in water may account for a large fraction, up to 90%, of a ship's total resistance. The highest values occurring for large full hull forms, such as tankers or bulk carriers, and for slow steaming ships. Air Lubrication Systems (ALS) can provide a substantial reduction of the dynamic viscosity thanks to the presence of air bubbles injected into the boundary layer formed at the ship's hull surface.

Some ALS are already installed on ships but they require pumping compressed air beneath the hull. The deployed industrial compressors use a large fraction of the energy gain from the friction reduction provided by the ALS. In project RETROFIT55, the Armada Technology's Passive ALS (PALS) will be further developed. The PALS exploits fluid physics and a Venturi system to minimize the power required for bubble production and injection (Fig. 1). To date, PALS has been tested in a cavitation tunnel using a flat steel plate to mimic the hull bottom over a range of speeds and drafts.

Scale models of a container ship and a bulk carrier will be tested at the CNR "towing tank". Computational Fluid Dynamics (CFD) work will be undertaken on both vessels to determine the optimal number and location of the PALS injectors and subsequent insertion into the model's hulls. The test matrix will include: "base line" conditions, system fitted but non-operational, operational with all injectors in use, and with several combinations of the injectors either non-operational, injecting an air water mix or water only into the boundary layer. The test will allow to determine PALS optimal drag reduction performance at various speeds and drafts on both vessel types and to correlate PALS performance in the towing tank with that predicted by the CFD calculations.

Regulatory compliance will be assured along the lines of the Approval in Principle (AIP) process of RINA (RINA GUI19) entitled "Guide for Approval in Principle of Novel Technologies". Accordingly, RINA GUI015 "Guide for Risk Analysis - GUI015" will be used to identify, rank and control hazard and/or failure modes.

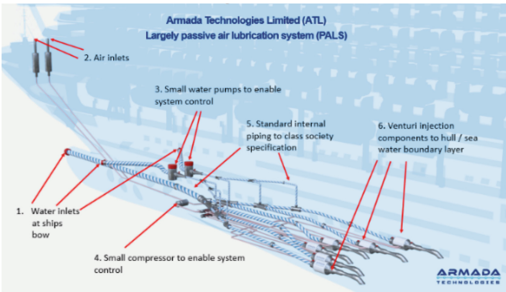

Fig. 1. Internal piping of the Armada Air Lubrication System - Reproduced with permission from Armada Technologies, copyright Armada Technologies, 2024.

2.2 Wind Assisted Ship Propulsion

Although not always predictable and available en-route, wind can provide a substantial contribution to a ship's thrust. Project RETROFIT55 contributes to the development and integration of two standardized WASP technologies known as "Semi Rigid Wing" by Advanced Wing System Ltd and Rigid eSAIL® developed by Bound4Blue (Fig. 2). Both systems aim to reduce the times and costs of the installation.

For Semi Rigid Wing, a modular system on a 40' ISO container footprint will be developed to fit with the supporting structural frame. An abatement solution will be developed to allow for a fast stowing of the sails when approaching the port areas. The modular system shall encompass all the power, actuation and control systems required for full autonomy. A detailed risk assessment will be conducted, based on the existing preliminary designs to identify areas where risk can be mitigated, or risk management plans could be developed. A scale model will be built to allow testing of operational systems to provide some validation ahead of detailed design before moving to the design and built a land-based solution with about 20 m mast used for demonstration.

For eSAIL®, attention will be devoted to the design of a standardized family of steel reinforcements for use in retrofitting of a wide range of vessel types. Those will be used to ensure a right force distribution over hull and bow, the lowest weight, and a minimum footprint on the vessel. Since rigid sails use Programmable Logic Controller (PLC) and motor friction joints, the installation on ships with potentially explosive environment and hazardous areas, such as oil tankers, crude carriers, LNG, LPG and other chemical tankers in which ATEX standards have to be satisfied. The eSAIL® systems will be modified and/or relocated to accommodate for such risks.

2.3 Hydrodynamic Optimization

The optimization of the ship and propeller design will be conducted holistically, i.e. by considering all elements that may influence ship performances. The ship may need to be reshaped in case suitable routing allows reduced operational speed. It is expected that the bow part of the ship hull and the propeller are to be redesigned to better fit to actual or modified speed. The presence of sails, beside contributing to the thrust, may induce a change in ship seakeeping performance and route keeping, to be accounted during design optimization. Hydrodynamic optimization will be used and further extended to account for the propulsion efficiency in wind and wave conditions. High fidelity fluid dynamic solvers, potential flow solvers, reduced order models, will be used to explore the broadest set of design variables and minimize uncertainty in the results.

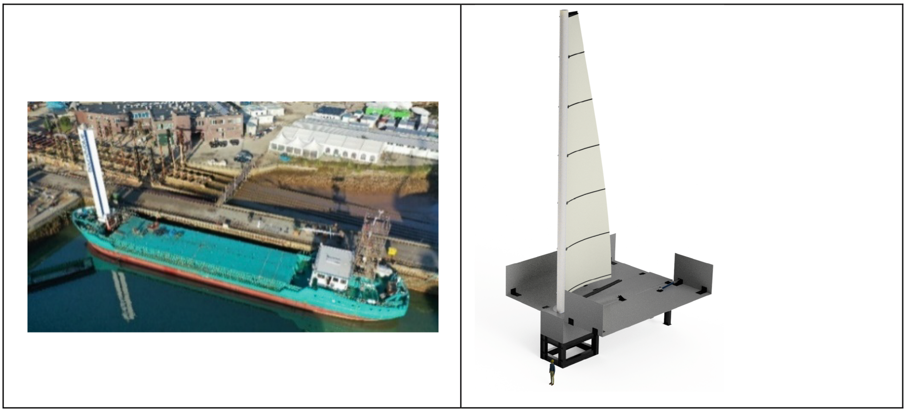

Fig. 2. Left: Rigid eSAIL® system - Reproduced with permission from Bound4Blue, copyright Bound4Blue, 2024; Right: sketches of the Semi Rigid Wing installation (Reproduced with permission from Advanced Wing Systems, copyright AWS, 2024.

2.4 Operational Optimization

A significant reduction of the fuel consumption and GHG emissions can be achieved by introducing an improved operational management. RETROFIT55 aims to introduce an improved weather routing systems that considers the final ship design and the retrofitting options available (e.g. sails, speed requirements, etc.). A key aspect will be the evaluation of the cumulative effect of the measures applied under off-design conditions.

The project will also develop a framework for the continuous monitoring of the ship performance status, and targeting at her hull and propeller aiming at supporting condition-based maintenance. The analysis will be based on machine-learning models exploiting high-frequency operational data. This framework could be used to evaluate the effectiveness of the new coating solutions (e.g. silicon-based anti-fouling coatings). The weather routing decision support system [1] will further expand to account for the use of energy saving devices. Fuel oil consumption under realistic weather conditions and for an expected range of service profile will be assessed with and without the combined effect of route and speed optimization. The aim will be to quantify the benefit of the examined retrofit measures. Seakeeping will be also taken into consideration.

The project will develop a framework to evaluate the ship conditions based on the high-frequency operational data. Such approach will allow for plan maintenance in advance. It may be also used to evaluate more precisely the effectiveness of the new coating solutions (e.g., silicon-based anti-fouling). The weather routing decision support system [1] will be further expanded to account for the use of energy saving devices.

Specifically, the fuel oil consumption under the effect of realistic weather conditions and for an expected range of service profile (ship's speed and loading condition) will be assessed with and without the combined effect of route and speed optimization in order to quantify the benefit of the examined retrofit measure. Safety aspects will be taken into consideration in weather routing optimization.

2.5 Energy Management and Electrical Systems on Board

Significant improvements in the efficiency and GHG emissions reduction can be achieved by a smart management of systems producing and consuming energy on board existing ships and by proposing new solutions. Before retrofitting a ship plan, it is essential to identify the energy system options and operational requirements. Today, in most cases, the power plant does not operate optimally neither during navigation, nor in port. This may lead to high fuel oil consumption and air emissions. An accurate analysis of power-related data shall enable better quantification of potential improvements in terms of energy efficiency and in the design of alternative solutions (e.g., use of hybrid battery systems). The analysis will cover both the main power plant and the auxiliaries (e.g., boilers, air conditioning systems, bow thrusters, etc.). The main engine(s) set point will be optimized by considering the contribution of a shaft generator system which, in turn, can either supply the ship electric grid or an energy storage system. The same can be used as a boosting device to the main propulsion engine to improve the environmental footprint of the ship, particularly in ports. Carbon-free solutions such as fuel-cells power installation or photovoltaic panels are valuable alternatives for retrofitting. Yet, such installations need batteries to adapt to the varying power demands and to store the solar energy. Design for retrofitting studies will be conducted to ensure the fitness for purpose of such solutions.

Recent developments in the field suggest that there is room for substantial efficiency improvements via the introduction of smart energy management systems. Consequently, the on-board micro-grids will be re-defined to ensure the required power quality, a high continuity of service and a simple and lightweight electrical plant, without compromising safety, maintainability and environmental protection. Depending on the specific ship type and use, the best solution between integrated power systems (IPS) and distributed generation will be considered, exploiting PV generators and fuel cells purposely dislocated in the ship optimizing the power load balance. The most suitable power grid topology (e.g., AC, DC, hybrid AC/DC) will be selected based on significant metrics and numerical simulations. Hence, the power train and on-board smart micro-grid solution developed will be integrated and analyzed both theoretically and numerically. Finally, an energy management system (EMS) will be developed to optimize specific target functions.

3 Web-Based Catalogue

Each of the retrofitting options discussed above, together with specific KPIs based on a life-cycle analysis, will be described in terms of surrogate models that will feed a decision support system that is the backbone of the web-based configurator. The system, specialized for a few use cases, will be accessible from a wide community of users, such as shipyards, operators, owners, equipment and solution providers, classification societies, public bodies and consultants that support the community in selecting the right combination of retrofitting solutions for a given ship within its operational profile.

The web-based system will allow an easy integration of additional and/or alternative solutions over time. It will support the selection of single solution but also the intelligent selection of a combination of solutions. The ship model will be made such that external companies and/or solution providers can enter their data. These data may come from other projects in the same field or from single system providers that take an interest to make available their retrofitting solutions from a technical point of view. A GUI component will allow to select various criteria regarding the vessel type, operational profile and other relevant "before-retrofit" state conditions such as propulsion plant, hydrodynamics, etc. Furthermore, the selection of overall goals such as the emission reduction, costs and/or downtime will ensure the prioritisation of potentially numerous feasible retrofit solutions. The actual processing of the entered information regarding the target vessel to be retrofitted will be carried out by a configuration service providing a knowledge-based engine which will search the catalogue accordingly, checking any applicable constraints and determine the top-most relevant combinations as proposed solutions. A demonstration will be set up during the last year of the project in order to show the benefit of the web-based configurator via the project's application.

Naturally, any web-based service needs to be maintained, extended and improved, steadily growing data, resources and the community of users and providers, giving benefit to all parties while observing their intellectual property rights, the competitive advantage of all participants, their trade secrets and cyber-secure management of data.

4 Conclusions

The RETROFIT55 consortium aim to address the objectives the EU WATERBORNE Strategic Research and Innovation Agenda (SRIA), and that of th ZEWT partnership in particular, with focus at design for ship retrofitting. The project explores solutions for improved ship efficiency (e.g., PALS, Smart Energy Management systems), holistic operational optimization strategies, as well as the exploitation of green and sustainable marine propulsion (e.g., WASP, Fuel Cells and hybrid systems). Each of the retrofitting options is fed into a digital web based decision support system for use by shipyards and ship operators [2]. It is envisaged that the project shall develop and demonstrate solutions that may have the potential to reduce fuel consumption by at least 55% before 2030 as compared to 2008. These objectives are well aligned with the European Union and IMO targets for environmentally sustainable shipping.

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Efficient Air Conditioning of Battery-Electric Multiple Units (BEMU): Modeling and Optimization

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Abstract. The power required for heating, ventilation and air-conditioning (HVAC) of the passenger compartment in BEMU strongly affects the capacity and lifetime of the battery. Accordingly, 11 different measures for reducing the energy demand of HVAC are presented in this paper. The measures are investigated using Dymola models of a thermal car body to determine the energy saving potential as well as the effects on the vehicle. Reducing the amount of fresh air while complying with CO_2 limits and using a heat pump are efficient measures to reduce the annual energy demand for the HVAC system by 62% or 48%, respectively. In addition, a control-based, catenary dependent HVAC operating strategy is being developed that decisively reduces the load on the battery during dynamic operation. This approach is particularly suitable for straightforward implementation since no design changes to the vehicle are necessary.

Keywords: railway vehicles · battery electric multiple unit · HVAC systems · thermal management · air conditioning · system modeling

1 Introduction

In the BMDV-funded (Federal Ministry for Digital and Transport in Germany) project MOSENAS, the German Aerospace Center (DLR) is working together with Stadler Rail to design and develop a modular and scalable battery storage system (see Fig. 1). This system is intended for use in battery-electric multiple units (BEMU) on partially electrified rail lines. Particular attention is also paid to the issues of operational suitability (e.g. usable range), cost-effectiveness and compatibility with the charging infrastructure.

The design of the battery capacity is largely dependent on the energy demand of the vehicle. This in turn is influenced by the auxiliary consumers, which account for up to 30% of the total annual energy demand [1]. The largest share of the auxiliary consumers is caused by the heating, ventilation and air conditioning (HVAC) of the passenger compartment, which is why research is being conducted into possibilities and

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Fig. 1. Modular, scalable energy storage in the MOSENAS project

technical innovations for reducing this energy demand [2, 3]. In the MOSENAS project, the energy demand for HVAC in rail vehicles was determined and new measures for reducing this energy demand were developed and evaluated.

2 Methodology – Definition of Measures and Modeling Setup

Definition of Measures

In the first step, 11 measures were defined that offer the potential to reduce the energy demand for the HVAC system. These measures are:

M1: Free cooling
M2: Passenger rate-dependent fresh air volume control via CO_2 content
M3: Direct use of recuperated energy for HVAC system
M4: Modified heat transfer through the outer wall of the car body
M5: Variation of leakage air flow to the environment
M6: Utilization of the temperature tolerance ranges of DIN EN 14750
M7: Change of setpoint temperature depending on catenary availability
M8: Variation of the vehicle category of DIN EN 14750 (A or B)
M9: Variation of the heat capacity inside the vehicle
M10: Use of a heat pump
M11: Waste heat utilization of the battery

The measures mentioned can be partially combined for the simulations, since similar parameters are changed. M1 investigates how an increased amount of fresh air to be introduced into the vehicle can be used for cooling at low outside temperatures. For that, fresh air is not processed by the HVAC system. M2 investigates to what extent the fresh air volume can be reduced without falling below the CO_2 limits, since current limits of the fresh air volume from DIN EN 14750 are fixed without taking the CO_2 content into account. Both M1 and M2 are consequently investigated by varying the amount of fresh air.

M3 investigates whether there are energetic advantages if the recuperation energy is used directly in the HVAC system. This avoids conversion losses in the vehicle.

M4 determines the effects of a different heat transfer coefficient, which can be realized, for example, by better insulation of the outer walls in the car body.

M5 explores how a modified air leakage flow affects the energy demand of the HVAC system. The leakage air flow enters and leaves the car body through several openings as it is not gas-tight.

M6 and M8 again investigate similar parameters. In M6, the variation of the setpoint temperatures is investigated using the characteristic curves from DIN EN 14750. Here, an upper and lower limit as well as a recommended curve are given (see Fig. 2 left). The characteristic curves also vary for vehicle categories A and B, so that the change in the curves due to the vehicle category is examined in M8. Category A represents regional trains while category B will be applied mainly to metro vehicles. Following M6 and M8, M7 considers the dynamic change of these characteristic curves under changing catenary availability in vehicle operation.

M9 investigates how varying the thermal capacity of the car body affects the energy demand. Thermal capacity indicates how much heat can be stored in the car body.

M10 studies the effects of heat pump use. Here, the heat pump can be used for the full part of the heating capacity, or only for conditioning the outside air.

M11 considers to what extent waste heat from the battery can be used to heat the passenger compartment.

Definition of Boundary Conditions

In order to investigate the measures presented, the boundary conditions for the simulation must be defined. The climatic boundary conditions for rail vehicles are specified in DIN EN 50591. For this purpose, 16 operation points (OP) are defined, which consist of the ambient temperature, ambient humidity, solar radiation and passenger rate. In addition, time periods are specified as to how often these OPs occur annually in order to determine an annual energy demand. In addition to the normalized OP, three further points were defined to investigate extreme climatic conditions. These points, as well as the two extreme climatic cases from DIN EN 50591 can be found in Table 1.

Table 1. Operating points for extreme weather conditions

OP	1*	2**	3	4	5
Ambient temperature in °C	−10	35	40	−20	−20
Ambient relative humidity in %	90	50	90	90	90
Solar radiation in W/m^2	0	700	0	0	0
Passenger rate in %	0	100	100	100	0

* OP1 and ** OP7 of DIN EN 50591

The boundary conditions on the vehicle side were specified by Stadler. A 3-car BEMU serves as the reference vehicle. The target values for fresh air and temperature control are based on DIN EN 14750 (see Fig. 2 left). While many measures were investigated in stationary simulations, dynamic simulations had to be used for M7 and M9. A daily driving cycle of a regional train in northern Germany was selected as the trackside boundary condition.

Modeling Approach

A thermal car body model (TCBM) from the German Aerospace Center (DLR) was used to investigate the measures presented. The model is created in Dymola and is based on a validated TCBM from Shift2Rail project FINE-2 [4]. The overview of the model is shown in Fig. 2 on the right. Centrally, the cross-section of the car body is shown. Here, the vehicle-side parameters are defined. On the left side are the model inputs in the form of the climatic boundary conditions. The output parameter is the electrical energy demand of the car body. The model is used for both stationary and dynamic simulations. In the dynamic simulations, the velocity-dependent convection at the outer wall of the car body leads to a dynamic behavior. For this, the trajectory of the vehicle has to be given as a further model input.

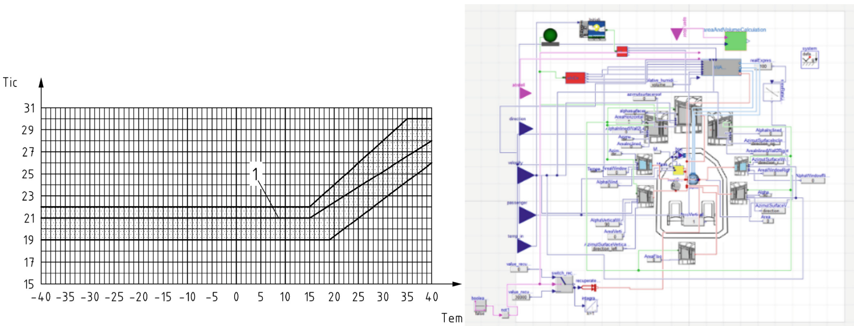

Fig. 2. Left: Set point for the temperature in °C in the passenger compartment (Tic) as a function of the outside temperature (Tem) in °C – Upper, recommended (1) and lower curve of DIN EN 14750, Right: Dymola surface of the thermal car body model (TCBM)

3 Results – Evaluation of the HVAC Optimization Measures

The measures presented to optimize the HVAC systems in BEMUs are evaluated below. For this purpose, the energy demand of the HVAC system was calculated in both stationary and dynamic simulations.

During the investigations, it was found that in the reference vehicle the recuperated energy can be completely absorbed by the batteries during the braking phase. Likewise, qualitative investigations of M11 revealed that the utilization of the battery waste heat is probably only possible in a meaningful way on the car on which the battery and the battery thermal management system are concentrated, which is only one car in the reference vehicle. Transferring the heat to all the other cars is critical in terms of moving hydraulic lines and heat losses along the length of the line. Accordingly, measures M3 and M11 have no or very little influence in the present case, so that they will not be described further in the following results.

Stationary Evaluation of Energy Efficiency Measures

The evaluation of the measures is based on the annual energy demand for HVAC. The measures can be divided into control-based measures and design-based measures. The control-based measures M1, M2, M6 and M8 do not require any physical changes or new components for implementation. However, measures M4, M5, and M10 can only be implemented if design changes are taken on the vehicle and thus tend to be costlier than the control-based measures.

When varying the amount of fresh air in M1 and M2, it can be seen that the increased amount of fresh air in M1 due to free cooling results in a drop in the energy demand by 14% of the reference value for OP3 and OP4 of DIN EN 50591. These OP are particularly suitable for the application of free cooling, since here the temperature difference between the interior car body and the environment is relatively small. In M2, lowering the fresh air volume flow beyond the DIN EN 14750 limits to 4 m^3/h per person shows a reduced annual HVAC energy demand by 62%. With the volume flow of 4 m^3/h, the calculations show a CO_2 concentration below 5000 ppm, which is the defined boundary in the technical specifications for interoperability (TSI).

M6 shows that using the lower temperature setpoint curve of category A results in a reduction of the annual HVAC energy demand by 22%. An optimized temperature setpoint curve that selects the lower setpoint heating cases and the upper setpoint in cooling cases reduces the HVAC energy demand even further by 32%. Combining this measure again with M8 and selecting vehicle category B with an optimized temperature setpoint curve reduces the annual HVAC energy demand by 36%.

When examining the design-based measures, M4 shows that reducing the heat transfer coefficient by 26% of the baseline value reduces the annual HVAC energy demand by 18%. M5 shows that completely preventing leakage in the car body reduces the annual HVAC energy demand by 16%. The use of the heat pump represents the design-based measure with the greatest potential savings by reducing the annual HVAC energy demand by 48%.

Dynamic Evaluation of Developed HVAC Operation Strategy

As described above, the evaluation of measures M7 and M9 requires a dynamic approach. Accordingly, they were combined with measures M6 and M8 to form an optimized control strategy for the HVAC system in the vehicle. The temperature setpoint is adjusted depending on the catenary availability and the ambient temperature. Under catenary, the HVAC power is maximized by selecting the maximum setpoint curve in the heating case and the minimum setpoint curve in the cooling case. In this way, the car body can be "charged" within the thermal comfort and store thermal energy for the catenary-free operation (CFO). In the CFO, the minimum HVAC power is demanded. This is implemented through the use of the minimum setpoint in heating mode and the maximum setpoint in cooling mode (see Table 2). The goal of this strategy is not necessarily to reduce the overall energy consumption from the catenary, but mainly to reduce the energy demand at the battery storage as battery costs and aging are a highly sensitive parameter for the BEMUs.

Table 2. Optimized control strategy for the HVAC system depending on catenary availability

Catenary	Heating case	Cooling case
Available	Max. setpoint temperature	Min. setpoint temperature
Not available	Min. setpoint temperature	Max. setpoint temperature

The implementation of the optimized HVAC control strategy HVAC in the simulations shows that the energy demand for the HVAC system in OP1 to OP5 decreases between 1.3% and 4.3% compared to the reference operation of the HVAC system for extreme weather conditions (see Table 3). At the system level, it can be seen that the energy demand for the vehicle in increases minimally in OP2, despite the reduced HVAC energy demand. This is related to the increased system losses due to the power increase from the catenary. Overall, however, it shows a reduction of up to 2.6% in the equivalent full cycles in the battery storage system. Thus, it is shown that the optimized HVAC operating strategy contributes to the relief of the battery storage.

Table 3. Comparison of the energy consumption with and without optimized HVAC control strategy for the HVAC system only and the overall vehicle in the daily driving cycle

OP (see Table 1)	1	2	3	4	5
Energy consumption HVAC	−3.9%	−1.3%	−2.7%	−4.3%	−3.0%
Energy consumption vehicle	−0.9%	+0.2%	−0.4%	−1.1%	−0.8%

Conclusion

There are a variety of measures to reduce HVAC energy demand in BEMU. The reduction of the fresh air volume depending on the CO_2 concentration is the most promising control-based measure among the presented ones with a reduction of energy demand by 62%. For this, however, the set points for fresh air flow in DIN EN 14750 must be reset. The use of a heat pump represents the most promising design-based measure with a reduction of energy demand by 48%, although it is costlier to implement. The optimized dynamic HVAC operating strategy depending on the catenary availability also offers the possibility of decisively relieving the battery storage, while complying the boundary conditions from DIN EN 14750.

Acknowledgement. The research results presented here were developed as part of the project MOSENAS (Modular Scalable Energy Storage for Sustainable Local Passenger Rail Transport), which is funded by the BMDV (Federal Ministry for Digital and Transport in Germany) and coordinated by NOW GmbH.

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Exploring the Potential of Smart Charging for Electric Vehicles: Insights from USER-CHI Project

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Abstract. Transitioning to electric mobility presents economic and technological challenges. In response to some of these challenges, the USER-CHI project has deployed a Smart Charging tool to implement intelligent charging strategies in the infrastructure network. Smart charging emerges as a key enabler to unlock the charging infrastructure deployment since it reduces their cost and facilitates the integration of renewable energies. This paper presents an analysis of the Àrea Metropoliana de Barcelona charging infrastructure utilization and demonstrates how the application of smart charging strategies can reduce the required power capacity while maintaining service quality. The proposed strategies enable operators to optimize energy-related costs, enhance the utilization of renewable energy sources, and actively participate in smart grid management. The analysis of charging session data reveals that longer sessions tend to have lower average power ratios, suggesting that the proposed strategies are more effective for locations with longer EV stays. Through simulations, the paper illustrates a substantial reduction in required power capacity when smart charging strategies are implemented. This research underscores the potential benefits of smart charging strategies for both Charging Point Operators and grid planners by reducing capacity-related costs and facilitating the deployment of new EV charging infrastructure. The ongoing USER-CHI project aims to further validate these strategies across various European pilot sites with diverse infrastructure sizes and optimization use cases.

Keywords: Charging infrastructure · Electric Mobility · Smart Charging

List of Acronyms

USER-CHI	Innovative solutions for USER centric CHarging Infrastructure
EV	Electric Vehicle
EU	European Union
AFIR	Alternative Fuels Infrastructure Regulation
AMB	Àrea Metropolitana de Barcelona
SMAC	SMArt Charting tool (USER-CHI product)
CPO	Charging Point Operator
EVSE	Electric Vehicle Supply Equipment

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OCPI	Open Charge Point Interface protocol
SoC	State of Charge of the battery (%)
V2G	Vehicle-To-Grid

1 Introduction

As the most energy-consuming sector in Europe [1], and the main cause of air and noise pollution in cities [2], the transport sector needs to tackle a profound decarbonisation. Sustainable forms of road transport are essential for achieving the EU's climate, zero pollution and energy efficiency objectives. Among these, the electric vehicles support the decarbonisation of transport and help achieve the EU-wide target of reducing net greenhouse gas emissions in line with the European Climate Law [3].

However, the shift to electromobility entails some technological challenges like the public charging infrastructure cost-effectiveness, the grid capacity issues or the maximum use of renewable energies. These will become even more relevant with the expected increase of fast charging points established by the new AFIR [4].

Considering that the public charging points are increasingly necessary to enable wider EV uptake and the challenges mentioned above, the Àrea Metropolitana de Barcelona (AMB), in the framework of the USER-CHI project,[1] is testing a Smart Charging tool (SMAC) in order to apply smart charging strategies in their charging infrastructure network aiming to reduce the requested power but maintaining the quality of service. SMAC is a tool that facilitates adoption of smart charging strategies to CPOs via OCPI open protocol, making use of data provided by both CPO and EV drivers to ensure fulfilment of charging requirements at minimum cost.

The provided smart charging strategies will help the operators to optimize their energy-related costs, enabling a better utilization of renewable energy sources and allowing their participation as active actors in the smart grid management. They will also help to speed up the charging infrastructure deployment by reducing the grid stress.

This paper presents the analysis of use of the AMB charging infrastructure and shows how applying the smart charging strategies provided will reduce the required power capacity for the charging infrastructure.

2 Methodology

The presented analysis is based on data extracted from the Charging Point Operator (CPO) backend software of AMB, for the year 2022. The analysed dataset contains information about 55 873 charging sessions that took place in the network of EV chargers, which was composed by 27 locations, each one with 1 to 3 EVSEs, accounting for 59 EVSEs in total.

[1] This project has received funding from the European Union's Horizon 2020 research and.innovation programme under grant agreement No 875187, https://cordis.europa.eu/project/id/875187. Website: https://www.userchi.eu/.

This analysis employs the nomenclature of elements as specified by the OCPI specification [5], namely:

- Connector is a specific socket or cable available for the EV to make use of.
- EVSE is the part that controls the power supply to a single EV in a single session. An EVSE may provide multiple connectors but only one of these can be active at the same time.
- Location is a group of one or more EVSEs that belong together geographically or spatially.

3 Proposed Smart Charging Strategy

The USER-CHI project proposes and implements a smart charging strategy under the umbrella of the product SMAC [6, 7], a software offering Smart Charging-as-a-Service targeted to CPOs, and based on OCPI 2.2.1 communication. This service allows CPOs to outsource infrastructure-level optimization with different degrees of freedom, adapting to the different possible contexts where EV chargers are installed. Additionally, it enables CPOs to become active actors in the smart grid ecosystem, by analysing their flexibility to facilitate their participation in local flexibility markets. In order to perform the optimization, SMAC utilizes data from the infrastructure –capacity (kW), demand (kWh), generation (kWh), nominal charge/discharge power per connector (kW), energy price (€/kWh) – as well as from the EV drivers – battery capacity (kWh), SoC (%) and time-to-charge requirements. Optimization has the objective of providing the set of charging profiles to the EVSEs that fulfil the charging requirements (energy supplied and time horizon to finish the charge) of all connected vehicles with the minimum cost (both energy- and capacity-wise).

4 Results

4.1 Main Findings on Usage Indicators of the Charging Infrastructure in AMB

In order to validate our base hypothesis, the analysis quantifies several indicators that describe the usage of the charging infrastructure in the AMB. Analysis of the data shows that, due to the fact that the infrastructure is used to offer public services, duration of the charge sessions is generally low – with approx. 75% percent of all charging sessions taking less than 45 min. On the other hand, values accounted for the average to nominal power ratio reveal that, in the 75% of the sessions, EVSEs would have potential to reduce power to about 60% without impacting the provided service.

4.2 Evaluation on Potential for Active Power Reduction Using Smart Charging

From the previous indicators, two particular findings are relevant in order to evaluate the potential for active power reduction using smart charging strategies: the duration of the charging sessions, and the average to nominal power ratio per charging session.

The analysis of the correlation between those two indicators shows that longer charging sessions tend to show lower average to nominal power ratios. Linear regression over

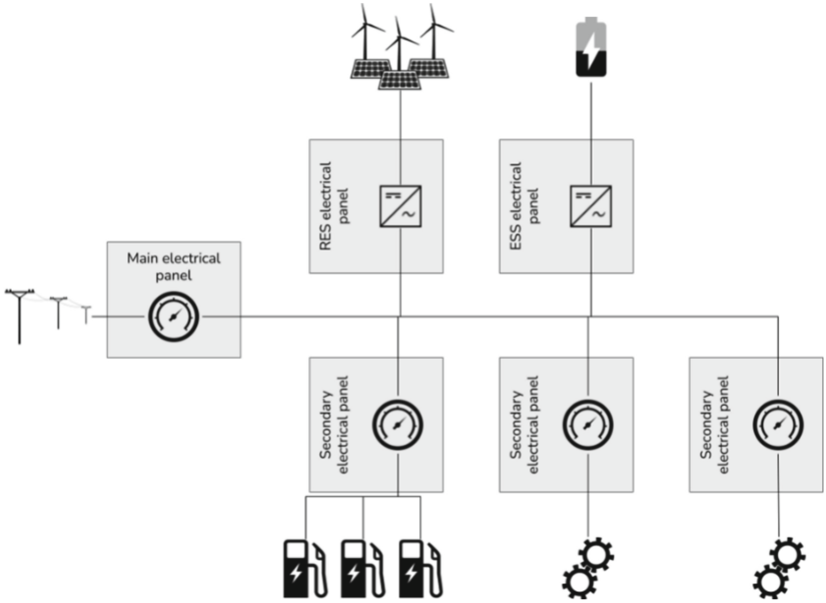

Fig. 1. Potential elements considered by infrastructure-level optimization.

Table 1. Summary of usage indicators of the charging infrastructure in AMB.

Indicator	Q1 (25th percentile)	Median	Q3 (75th percentile)
Duration of charging sessions	25 minutes	32 minutes	46 minutes
Daily occupancy of EVSEs	1.72%	2.26%	3.23%
Daily charging sessions per EVSE	2	4	8
Energy delivered per charging session	3.7kWh	8.5kWh	17.4kWh
Average to nominal power ratio per charging session	16.39%	29.56%	58.22%

those indicators reveals that, in average, ratio is lower than 40% and shows a trend of reduction of 1.32% for every extra hour of duration. This fact means that the proposed strategies will be more effective in those locations with usage patterns that indicate longer stays of the EV drivers.

More in detail, data of December 2022 corresponding to 619 charging sessions taking place at locations 33 and 34 in Cornellà de Llobregat – accounting for 4 EVSEs which share a common supply point, and selected by AMB to perform field tests of SMAC in the scope USER-CHI project – has been analysed to obtain indicators of the potential to reduce the contracted power without affecting the service using smart charging strategies. The analysis consists in the evaluation of the hourly maximum power expected at the supply point feeding the 4 EVSEs. Contracted capacity of the supply

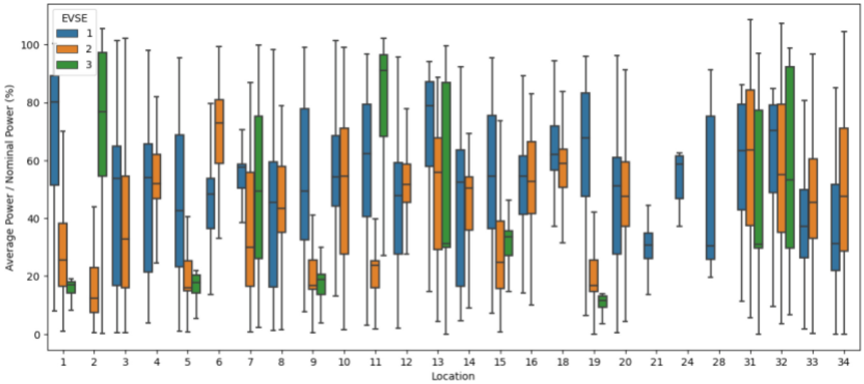

Fig. 2. Average to nominal power ratio per charging session.

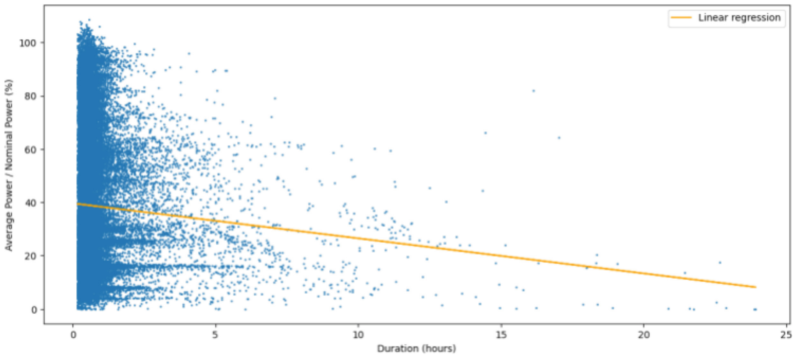

Fig. 3. Correlation between duration of the charging sessions, and the average to nominal power ratio per charging session.

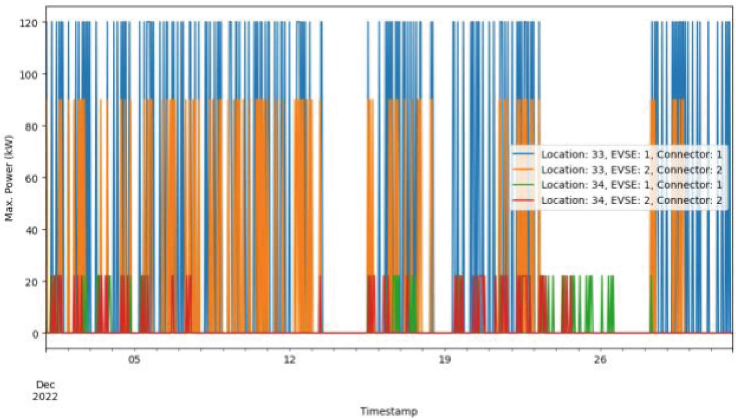

Fig. 4. Max. Power per EVSE and hour.

point is accounted as the sum of the nominal power of all EVSEs under its connection, as this is the Business-as-Usual scenario.

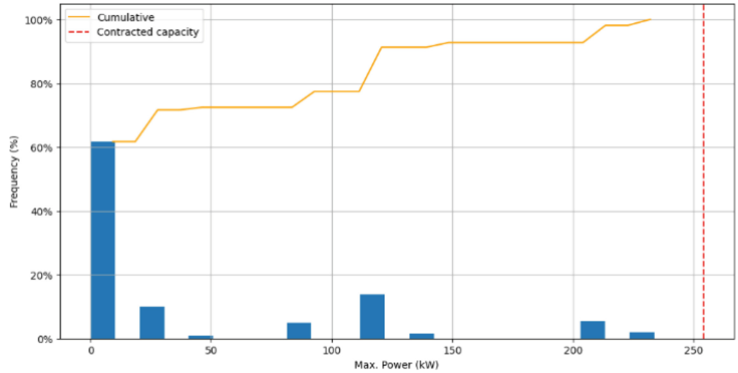

Fig. 5. Distribution of max. Power at supply point, compared to contracted capacity.

It can be observed that while contracted capacity is 254 kW, the supply point remains under 150 kW (59% of the contracted power) approximately 90% of the time.

In a second step of the analysis, data from actual charging sessions has been used as a basis to simulate the effects of applying SMAC strategies to the same locations and period of time. This second dataset has been used again to analyse the distribution of the power at supply point. The results show a clear reduction of the maximum power required at the supply point to provide the same level of service. Supply point would stay under 80 kW (31.5% of the contracted power) approximately 90% of time.

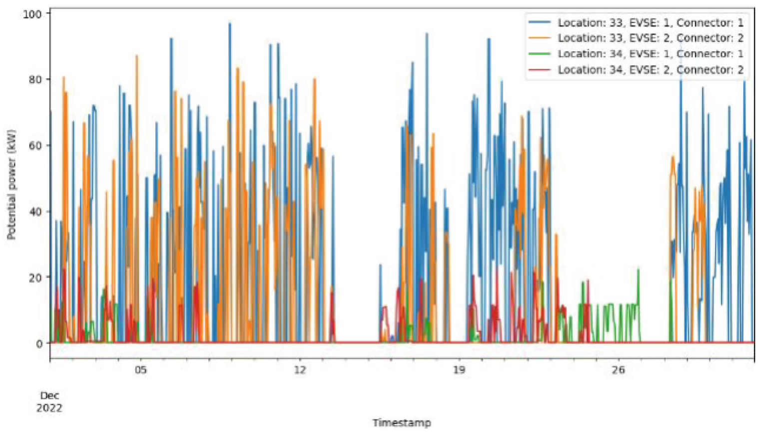

Fig. 6. Potential power per EVSE and hour with smart charging strategies in place.

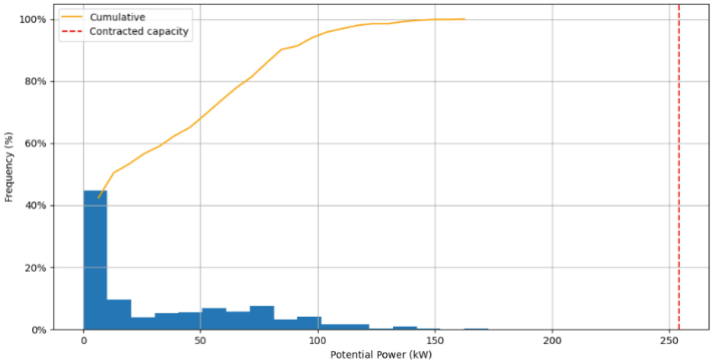

Fig. 7. Distribution of potential power at supply point with smart charging strategies in place, compared to contracted capacity.

5 Conclusions and Future Work

The presented analysis confirms the potential of the proposed smart charging strategies to reduce the required capacity for the EV chargers, which brings benefits both for CPOs (direct reduction of faced capacity-related fix costs) as well as the grid planner (lower capacity requirements per charger, which would facilitate the deployment of new EV charging infrastructure in existing grids).

In the framework of the USER-CHI project, SMAC will be tested in real environments in 5 different pilot sites, which will account for infrastructures with different sizes constraints and optimization use-cases – economic optimization, self-consumption, V2G. This will allow the collection of more data in order to validate the proposed strategies.

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Greening of Road Freight Transport

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Abstract. The international working group "greening freight" of PIARCs Technical Committee on freight investigated the strategies and measures to reduce greenhouse gas (GHG) emissions of road freight transport. In this article we will discuss the outcome of this work, i.e. a report that describes plans, strategies, and programs for greening, and distinguishes four approaches to reduce GHG emissions. It starts with a description of the global problem of human-induced climate change, depicting the situation in both HIC (high income countries) and LMIC (low- & middle-income countries) around the world. The first of the four approaches to reduce GHG emissions is about having less emissions from each vehicle. The second approach focuses on driving less and transport more goods per vehicle. The third approach deals with changing the transporting demand by vehicles that run on fossil fuels. The fourth approach is the reduction of transport emissions related to the construction sector. The report also presents lessons learnt from history, targets to help shape policy and solutions to implement policies and achieve objectives.

Keywords: Greening freight transport and logistics · Decarbonisation of Road freight · Policies and approaches

1 The Problem: Freight Contribution to GHG Emissions

Global warming is a problem we experience every day with rising temperatures, rising water levels, and more frequent extreme weather events. To keep the global temperature increase of 1.5° Celsius within reach, a package of measures must be implemented.

Freight transport keeps the global economy moving but contributes significantly to emissions of the greenhouse gas CO2. There are increased demands from various stakeholders that the climate impact from the transport system should be reduced and fossil fuels phased out. Also, pollution and noise are important issues, especially in urban areas. These challenges might benefit from measures for cutting CO2 emissions. UN's sustainable development goals include these areas, as well as the need for mobility and economic growth. As a major contributor to CO2 emissions, freight transport must also be a part of the solution.

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1.1 Targets for 2030

Road freight transportation was responsible for 2,4 billion tonnes of CO2 emissions in 2018. This constitutes 7% of overall global energy related emissions [1]. To reach the climate targets, it is likely that all transport modes and all countries must change to close to zero emission by 2050. Early emission cuts or even carbon capture (removing CO2 from the air) are crucial for staying within the 1.5-degree target. EUs member states and more than 20 other countries have updated their national 2030 targets to meet the global target of limiting warming to 1.5˚C. By 2030, many countries are dedicated to more than halving their emissions compared to 1990. To achieve a change of trend, new solutions must be cost-effective compared to today's transport solutions.

2 Solutions for Greening Freight Transport

In addition to plans, strategies, and programs for greening, we distinguish the following approaches to reduce greenhouse gas emissions.

Approach 1: less emissions from each vehicle	CO2 emissions are removed while the transport solution itself is kept
Approach 2: less driving and more goods per vehicle	Each vehicle can transport more goods per trip leading to less km driven and less emissions from road freight transport
Approach 3: change the demand for transport with Internal Combustion Engine (ICE) trucks	By diverting the demand emissions will be reduced
Approach 4: Transport related to construction sites	Reduce emissions concerning transport related to construction sites

2.1 Plans, Strategies, and Programs

To achieve the 2030 climate target, major changes to the truck fleet must take place during the 2020's for road freight transport. Countries, regions, states, and cities need **plans, strategies, and programs** for greening of freight transport. A toolbox of solutions is needed to solve the climate crisis. The working group greening freight has studied approaches made by nations, regions, and cities. We found that there are some universal traits to consider and refer to some good, but different examples underneath.

Most of these are described in further depth in the PIARC good practice collection for greening of freight transport [2]. The **European Green Deal** [3] and **Fit for 55** package [4] are examples of actions steering a whole continent towards carbon neutrality.

2.2 Approach 1: Less Emissions from Each Vehicle

By using zero emission or low emission vehicles the CO_2 emission are removed while the transport solution itself is kept, facilitating economic activity and trade. These vehicles can drive the same distance and transport the same amount of goods.

Zero Emission vehicles are most effective in this approach, but use of eco-friendly climate neutral fuels, eco-driving, and improved aerodynamics, engine performance, and rolling resistance will also reduce emissions. Change to alternative fuels demand available charging or filling infrastructure. At this stage, these measures are costly, making **bonus-malus** (positive and negative) **instruments** from governments necessary. Some measures like eco-driving are economically beneficial, as well as favourable for the climate, and they are achievable to implement in any country.

Zero emission vehicles and systems include battery-electric vehicles, battery swapping systems, fuel-cell electric or hydrogen vehicles, and electric road systems. The **power supply** must come from a **zero-emission** source, preferably a **renewable** source. The electricity production must be of a sufficient level. Reductions of emissions and other negative impact from the mining for minerals and production (batteries, metals, vehicles, infrastructure) are part of this approach.

2.3 Approach 2: Less Driving and More Goods Per Vehicle

More **efficient logistics supply chains** and allowing more goods per vehicle through longer or heavier trucks can both have the desired effect, and often with **increased profit** for the supply chain participants. Making road traffic pay for the **external costs** it is causing (such as CO_2 emission, local air pollution, accidents, noise, and congestion) can provide an efficient incentive for businesses to review their operations, e.g., increasing average truckloads and reducing the number of truck trips and mileage. Often weight restrictions and regulations must be modified to allow for this approach.

2.4 Approach 3: Change the Demand for Transport with Internal Combustion Engine (ICE) Trucks

Approach 3 is to change the demand for transport by internal combustion engine vehicles. By diverting the demand emissions will be reduced. More **efficient changes** between transport solutions and modal shift are examples of this approach. The continued use of roads but change from trucks or vans to bikes or small zero emission transport units such as autonomous delivery robots are other examples. **Policy regulations** are necessary to promote the shift to zero emission logistics. In city centres, regulations such as limited access times, weight or length limitations have already been in use for many years. These approaches can be economically beneficial, if the demand for transport is high enough and the logistic chains are efficient. This approach demands space that is often in demand for other city or passenger related purposes.

2.5 Approach 4: Reduce Emissions Concerning Transport Related to Construction Sites

The fourth and last approach we explore is to reduce emissions concerning transport related to construction sites. This approach has been chosen, because construction activities contribute with a **large share of CO_2 emissions**, and it is an important part of “circular economy model”. Soil, rocks, gravel, peat, and clay contributes the most tonnes transported, whereas materials and equipment had the highest emissions due to longer trips. It is estimated the **typical energy consumption breakdown** of a road construction project is 75% material production, 20% transport and 5% construction itself [5].As far as transport is concerned, in addition to the material, the equipment and personnel must also arrive on site. Approach 1 (2.2), 2 (2.3) and 3 (2.4) are all relevant for freight transport to and from construction sites. Introducing zero emission vehicles and machines are so far expensive measures. However, the potential for reducing emissions by demanding less transport and using less CO_2-intensive materials are high.

3 Conclusions

Conclusions from the PIARC working group on greening freight transport were drawn based on literature study, knowledge exchange during meetings (partly virtual) and a workshop (2022, Bordeaux, France). We processed these conclusions in three parts: lessons learned (3.1), targets to help shape policy (3.2) and solutions to implement policies and achieve objectives.

3.1 Lessons Learned

Targets for reduction of emissions are not always achieved. However, setting an ambitious target may have an effect, by accelerating a start. The freight transport sector needs to take the sense of urgency seriously, consider all measures available, continue researching, and sharing knowledge. Without proper financing of measures, policy measures are less likely to be implemented quickly enough.

Collaboration is key for getting best practices implemented. The public administrations and the private sector need to consider the problem from well-to-wheel and to fully include recycling and transport in the price of products and inform customers. There should be a strong awareness of the greenwashing risk - the misleading information about how environmentally sound a product or policy is in practice. There is still a need to enhance awareness of why societies and businesses need to continue using road infrastructure for freight transport. Freight transport is key to our modern way of living, and our economic model is based on transport dependent trade. When green solutions are also economically best for the decision maker, implementation is easier. Infrastructure for charging and filling alternative fuels (e.g., hydrogen, electricity) are a crucial provision.

The different transport modes' shares of traffic volume are quite stable over time. Over the last decades, the challenge of changing the modal split is tenaciously great, which is not fully realized by everyone. Even through extreme circumstances, such as the Covid pandemic, the energy crisis and the war in Ukraine, road transport dominancy does not change substantially.

3.2 Targets to Help Shape Policy

The most important responsibilities public authorities should shoulder are to set CO_2 emission reduction targets, secure knowledge, development, and regulations, initiate financing, and the necessary infrastructure, and spread the sense of urgency. Financed strategies, programs, and plans for greening can be **effective instruments** to be able to reach the targets set. Within their respective countries or regions, public authorities often are significant economic actors.

Especially in the initial stages of implementing new technologies, authorities can secure possibility and profitability for the early movers applying their purchasing power, regulatory authority, and infrastructural responsibilities. For greening transport, this includes measures to aiding the purchase and operation of low or **zero emission vehicles** (e.g., provision of charging stations, more lenient, direct subsidies to companies) and introducing contract conditions to make freight transport more sustainable. At the same time, authorities should make sure to explore the possibilities within the **traditional measures** such as eco-driving, fleet renewal, and transferal of goods.

Targets can conflict with each other. Therefore, it is so important to build policy on knowledge, to be aware on the consequences of choices. Authorities must choose wisely between broader measures that may slow the decrease of CO_2 emissions or even increase it (e.g., transferal of goods from zero emission trucks to diesel trains and ships using marine gas oil) and more direct measures for fast reduction, e.g., zero emission vehicles and nuclear power production. There is a need to communicate the sense of urgency, and to consider solutions for freight and passenger traffic together (e.g., in national, regional, and local transport and mobility plans).

3.3 Solutions to Implement Policy and Achieve Objectives

Crucial for tackling the climate problem is to have a good mix of technological solutions, political will, and awareness of cultural differences. There are already low and zero emission solutions available, and not one solution will solve the climate crisis alone. Cooperation between countries and sectors are crucial for success. One size does not fit all: there is a need for a whole toolbox. Benefit-cost ratios of measures taken and effectiveness of possible solutions are evolving fast.

To welcome effective solutions and innovations, it is recommended to regulate for technological neutrality, when possible. Technologies must be able to go through a cyclic process of policy making, financing, implementing measures, measuring effects, evaluation, and then repeat the process. Fail fast and implement successes. Learning from failure is equally important as learning from success.

Global warming will have tremendous negative impacts on many low and middle income (LMIC) countries due to their high dependence on natural resources and limited capacity to cope with the extreme effect of climate change. In addition, regions with more ambitious **decarbonising policies** may increase their competitiveness in the world market on behalf of regions with less ambitious policies, according to ITF forecasts. Increasing CO_2 taxes and CO_2 trading quotas are expected, as well as a customer demand for zero emission products and services. Two important questions are (1) what measures are most suitable for LIMC as a starting point, and (2) if new technology will allow them to leapfrog to zero or low emission and effective solutions for road construction and freight transport.

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Trend Scenarios for a Stationary Charging Infrastructure to Handle Direct Electric Road Transport in Germany

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Abstract. The German Climate Protection Act mandates a 65% reduction in greenhouse gas emissions by 2030 compared to 1990, aiming to achieve climatic neutrality by 2045. Within this context, the transport sector faces a pressing need for prompt and effective emission reduction strategies. Notably, heavy-duty vehicles represent a small subset of the overall vehicle population but contribute disproportionately to emissions. Despite this, Germany lacks definitive policies for emissions-reducing technologies. A variety of possible technologies struggle due to efficiency disadvantages, direct-electric heavy-duty vehicles (stationary charging points and electric road systems) have emerged as a promising solution. Initially, the study envisions a hypothetical scenario with a complete adoption of battery electric trucks for forecasting. Accurate planning of the requisite charging infrastructure hinges on a precise understanding of energy demands, both in terms of location and magnitude. This paper offers a concise outline of the essential architecture of the macroscopic traffic model needed for this investigation, coupled with the resultant local energy demands from heavy-duty vehicles across Germany. Building upon this model, three prospective trend scenarios are devised, embodying possible configurations for sizing stationary charging infrastructure, forming the core emphasis of this study. The results show that an expansion of 25,700–72,000 low-power chargers and 5,100–13,400 high-power chargers can meet the calculated energy requirements for 100% battery-electric road freight transport in Germany.

Keywords: charging infrastructure · battery-electric truck · electric road systems

1 Introduction

The German Climate Protection Act prescribes a compulsory reduction of 65% in greenhouse gas emissions by the year 2030, relative to the baseline year 1990, with the overarching objective of attaining climatic neutrality by 2045[1]. The transport sector, which has not yet made significant progress in reducing emissions, needs expeditious and efficacious strategies for emission reduction. Notably, the category of heavy-duty vehicles emerges as a promising opportunity for intervention, given that a disproportionate fraction of emissions emanates from a small vehicular cohort. Within the German

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context, substantive strides in delineating seminal policy directives toward prospective emissions-mitigating technologies remain elusive.

The joint research project ESOB-RKI of the University of Applied Sciences Erfurt and the Bauhaus University Weimar is therefore dedicated to the investigation of possible combinations of static and dynamic (via overhead lines) charging of electrified truck systems. Other technologies are not the subject of the investigation due to the efficiency disadvantages that currently exist [2]. Initially, a 100% adoption of battery electric trucks is hypothetically considered. To plan the requisite charging infrastructure aligned with demand, energy needs and locations are crucial. This article offers a concise outline of the macroscopic traffic model and resultant local energy demand for German heavy-duty vehicles. Three prospective trend scenarios are formulated using this model, centralizing on sizing stationary charging infrastructure – the core of this study.

2 Construction of the Transport Model and Derivation of the Resulting Energy Demand

2.1 Construction of the Transport Model

A model is employed to examine and assess the impact of diverse factors on a given system. In this context, a macroscopic transport model is utilized, comprising three constituent model components, thereby furnishing comprehensive insights into an entire transport framework while abstracting from individual vehicular elements.

Network Model

The network model represents spatial and temporal aspects of transport supply. It represents infrastructure such as roads, rails, and air routes. Temporal components encompass timetables, restrictions, and variables. In the ESOB-RKI project, focus is on trunk roads due to their computational advantage. The investigation extends beyond Germany to neighboring European countries, with analysis accuracy decreasing with increasing distance from Germany. The aim is to consider the effects of neighboring European countries as well as transit traffic affecting Germany. The network model was extended to incorporate targeted infrastructure projects by 2030. In addition to roads, the spatial structure of the model is represented by traffic cells, which serve as both source and destination of demand, each calculation refers to these cells. As in the case of the road network, the level of detail of the cells decreases with increasing distance from the study area, from NUTS3 to NUTS1. Demand data as part of the traffic flow forecast 2030 (TFF) is available for all cells implemented in the model, which can be fed into the model via the road network.

Transport Demand

In macroscopic transport modeling, the second major component alongside transport supply is transport demand, which results from a change of location such as commuting or shopping. In the context of the project, the focus is on freight transport, for which data is available as part of the TFF 2030. To ensure that all supply characteristics of the modes are represented in the TFF, intermodal network relationships were created from the individual networks of the modes [3].

A major challenge with TFF data is the lack of information on truck trips, so alternative sources are needed that allow the number of truck trips to be determined from weight information on freight movements. Specifically, the information related to annual tonnage shifts between traffic cells is transformed into a metric that quantifies daily truck trips. This transformation enables the calculation of daily energy requirements and, consequently, the determination of the necessary charging infrastructure.

An impact model can be derived from the two main model elements (network and demand) to estimate the effect of an electric road freight transport.

2.2 Energy Demand Forecast

Predicting energy supply needs and locations relies on regional energy demand forecasting. This methodology employs the established four-step model [4], a staple in transportation modeling and planning. The TFF has already implemented the first three phases projecting traffic volumes for 2030 (traffic generation), allocating traffic to cells (traffic distribution), and assigning modes (e.g., truck, train) (mode choice) of the four-step model. The fourth phase, route choice model, transfers transport to available supply, studying demand's route impact. Each truck optimizes routes for equal resistance, keeping travel time in check [5]. This process yields trunk road section load data. Energy demand (ED) is derived by multiplying section length, load, and a 1.3 kWh/km factor (average consumption), as seen in Eq. 1. Other studies note energy use between 0.8 and 1.94 kWh/km [6].

$$ED = Length * Load * 1{,}3\ kWh/km \tag{1}$$

ED relates directly to section load. Summing ED across structures determines demand for traffic cells and other spatial units.

3 Trend Scenarios for Stationary Charging

For the calculation of the total demand and the regionalized demand for stationary charging infrastructure, three trend scenarios are defined with regard to the expansion of public charging infrastructure.

3.1 Calculation Methodology

In order to determine the dimension of the charging infrastructure from the calculated energy requirements, a calculation methodology was developed that makes it possible to determine the necessary number of charging points.

The calculation variant compares the required total energy of a charging type with a mixed calculation based on a fixed travel distance assumption per charging process and the possible number of daily charging processes at the charging point (CP) (Eq. 2). In terms of the available charging technologies, a distinction is made within the project between low-power chargers (LPC) and high-power chargers (HPC). These differ mainly in the share of the total energy demand and the frequency of use of a charging point. The analysis is limited to public spaces; technologies that are used in private or semi-public spaces are not part of the study.

$$Number\ of\ CP(charge\ type) = ED * ED - Share/((distance * consumption) * usage\ CP) \quad (2)$$

To estimate the dimensioning of the charging infrastructure, the average energy demand per vehicle and charging type is determined. The number of CP required per charging type is also calculated from the product of the total ED and the share of the respective charging type, here a distinction can be made between HPC and LPC, divided by the driving distance between the charging processes, multiplied by the vehicle consumption and the frequency of usage per CP. For example, in the Medium Trend scenario HPC charging is assumed to occur after 300 km. This assumption is based on the distance a truck can travel in one piece before having to take a mandatory break after 4.5 h (Ø 66 km/h). Multiplied by an assumed consumption of 1.3 kWh/km, this results in a recharging requirement of 390 kWh. If the CP is used twelve times per day, 4680 kWh per day can be provided.

3.2 Lower Trend Scenario

The lower trend scenario envisions a situation necessitating the minimal number of public CP. The public charging infrastructure's overall portion is set at 30%, a reasonably realistic proportion seen in comparable studies [7]. Across all trend scenarios, the ratio of LPC-CP to HPC-CP remains constant at 30% LPC and 70% HPC. This scenario assumes a 350 km driving distance between charging sessions, implying a high average speed of nearly 80 km/h and an uninterrupted driving time of 4.5 h per truck trip, adhering to legal regulations. Despite having a greater share of HPC-CP, this lower trend scenario aims for fewer public CP compared to other studies. This is reinforced by a higher number of daily charging operations per point, assuming a usage rate of 14 times a day for HPC and 1.2 times for LPC. This estimate reflects the anticipation of mature systems and efficient charging management with full battery electric truck penetration. It should be noted that this scenario points to substantial private sector charging demand, which will not be further explored in this study.

3.3 Medium Trend Scenario

The medium trend scenario is intended to form the basis for the further modeling steps and calculations in the course of the project and, as can be assumed, lies exactly between the lower and upper trend scenarios. The total share of energy demand of the public charging infrastructure is 35%, which is between the common demand analyses and target values [7, 8]. The number of charging operations per CP (12 times per day for HPC and 1 time per day for LPC), again assumes technologies for better utilization. The travel distance between charging operations in this case is more conservatively estimated at 300 km; a lower average speed is assumed.

3.4 Upper Trend Scenario

In the upper trend scenario, an increased number of public CP is assumed. The total share of public charging infrastructure is 40%, which corresponds to the maximum shares assumed in other studies [8]. In parallel, with a significant share of non-public charging points, the number of required public CP (and thus the required space) reaches a maximum. The assumption of a reduced range of 250 km contributes to the CP maximization. Daily usage is further reduced in the upper trend scenario by assuming 10 times daily HPC usage and 0.8 times daily LPC usage.

3.5 Results

Table 1 and Fig. 1 show the results of the calculation of the number of public CP required for 100% battery-electric road freight transport in Germany. As expected, the results differ significantly from each other. With the assumptions made in the upper trend scenario regarding occupancy frequencies, shares of total energy demand and travel distances between charging operations, approximately 85,000 public CP are sufficient to cover the energy demand of a direct-electric road freight transport. This equals in detail 1.6 times the number of LPC-CP compared to the medium trend scenario and 2.7 times compared to the lower trend scenario. The number of HPC-CP in the upper trend scenario is a factor of 1.6 compared to the medium trend scenario and 2.6 compared to the lower trend scenario.

Table 1. Results of the charging point calculation (own calculations)

Trend Scenario	LPC-CP in Germany	HPC-CP in Germany
Upper	71.985	13.437
Medium	41.991	8.165
Lower	25.709	5.142

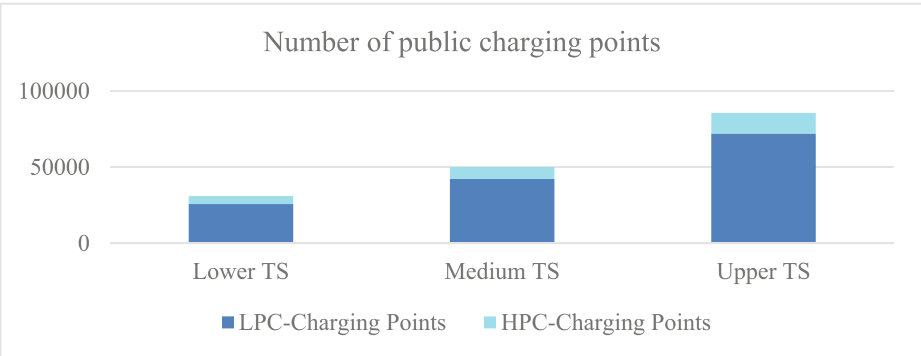

Fig. 1. Number of required public CP (own representation)

4 Conclusion and Outlook

This contribution established the groundwork for further exploration of direct electric road freight transport. The energy needs, derived using the traffic model, were utilized in three scenarios through the developed methodology. This approach aimed to offer a comprehensive perspective on design dimensions. Initial findings indicate substantial efforts required to establish the essential charging infrastructure for complete battery-electric road freight transportation. The total required charging points range from 30,000 to 85,000, highlighting the scale of the endeavor.

Subsequent to the assessment of the battery electric scenario, potential hybrid scenarios incorporating electric road systems are examined. Diverse target horizons are considered: the spatial coverage of an ERS system, achieving peak demand for an ERS system, and resolving existing parking challenges.

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Greenhouse Gas Emission Monitoring Tools in Freight Transport: A Status Analysis of Austrian Companies

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Abstract. The logistics sector is a significant contributor to global greenhouse gas emissions, which requires a thorough understanding of emissions for effective decarbonization, especially in the context of European transport policy. This study examines the emissions monitoring practices of Austrian transport companies. We conducted an online survey of 151 logistics stakeholders to identify current practices, the influence of transport modes usage, and barriers to adoption. Our results show a significant uptake of emissions monitoring tools by Austrian companies, with a notable potential for improvement, especially among road-dependent companies. The lack of comprehensive regulatory requirements emerges as a significant barrier to wider adoption. This study provides fundamental insights that pave the way for further research and strategies, while highlighting the challenges and opportunities of emissions monitoring in Austrian transport logistics.

Keywords: monitoring emissions · freight transport · CO2 reduction

1 Introduction

The logistics industry, especially transport logistics, is a major contributor to greenhouse gas (GHG) emissions that have a significant impact on the global climate. With current and impending climate disruption, it's critical to take proactive steps to reduce these emissions [1]. To meet the European Commission's (EC) target of "net zero emissions by 2050" [2], the sector needs to decrease its CO_2 emissions by roughly 3% each year until 2030 [3]. Hence, it's imperative for companies to gain a thorough understanding of their GHG emissions to facilitate the implementation of decarbonization strategies [4]. Unfortunately, companies face obstacles in effectively monitoring their emissions and taking action to reduce them [5]. In terms of investigating the implementation of emission monitoring tools or methods, there is a considerable research gap, given the lack of studies on the adoption of emission monitoring methodologies in enterprises [6]. The current approach to improve the monitoring of GHG emissions in the transport sector is based on the EC proposal for a unified regulatory framework for GHG emissions tracking *(CountEmissions EU)*. The aim is to promote the widespread adoption of a consistent and reliable GHG emissions framework, harmonized practices and ensuring

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consistency of GHG emissions accounting results across the transport logistics sector [7]. Therefore, this study evaluates the current status of Austrian companies with regard to the adoption of emission monitoring tools and methods in the field of transportation logistics. It also examines the relationship between the transport modes used and the propensity to adopt tools. Furthermore, this research examines the prevailing barriers that limit broader adoption.

2 Research Framework

In pursuit of the objective to investigate the existing landscape of emission reduction monitoring tools, it is imperative to initially assess the extent to which companies presently incorporate emission calculation tools or methods into their operations. However, the process of quantifying and monitoring emissions is inherently complex, requiring the consideration of a multitude of interrelated variables [4, 8]. As a result, there is a need to deploy robust methodologies designed to effectively monitor emissions. Paradoxically, the landscape is filled with a multitude of different frameworks and tools, each representing a solution for assessing, quantifying, and monitoring emissions [9]. This multitude of options has left companies with the challenge of selecting the most appropriate framework or tool for their specific needs [10]. Existing research on the adoption of emissions monitoring tools indicates that the majority of companies have not yet adopted such tools [9, 11]. As a result, we posit the following hypotheses [H1]: *Transport emissions monitoring tools show limited adoption by Austrian companies.*

In today's business landscape, companies, particularly those heavily reliant on transport modes known for their adverse environmental impact, such as road transport, face mounting pressure to actively track and disclose their emissions [12]. Given the significant emissions associated with road freight transport, it is reasonable to assume that organizations that predominantly utilize this transport mode may have a greater propensity to adopt emissions monitoring tools as a fundamental component of their decarbonization strategies [13]. Thus, we hypothesize [H2]: *Companies that rely only on road transport are more inclined to use emission monitoring tools.*

Given the complex network of transportation operations, effectively monitoring emissions from logistics activities is a daunting challenge [6]. A growing body of research underscores the need for clearly defined policies, disseminated through established legal channels, that establish the necessary standards for reporting emissions [5, 14–16]. In the absence of concrete legal guidance, companies may be reluctant to disclose emissions data due to concerns about potential legal repercussions associated with premature disclosure. [10]. This lack of legal and regulatory guidance creates a significant level of uncertainty in GHG emissions reporting [11]. Hence, we postulate the third hypothesis [H3]: *The main catalyst for the limited adoption of emissions monitoring tools can be attributed to the absence of a comprehensive legal requirement.*

3 Methodology

An online survey was conducted from March 16th to March 22nd, targeting a cohort of 1,600 Austrian stakeholders representing the comprehensive spectrum of the logistics industry. The outreach to these stakeholders was facilitated in collaboration with "VNL

- Vereinigung Netzwerk Logistik," a logistics association. The survey used a semi-standardized approach, primarily using closed and multiple-choice questions. It also included an open question to assess qualitative aspects. The questionnaire consists of three sections, namely demographics, transport modes and tools, as shown in Table 2 in the Appendix. A total of 151 questionnaires were fully completed and valid, resulting in a response rate of 9.4%. Table 1 shows the company demographics regarding size, branch and region of economic activities. Approximately three quarters of the respondents belong to large, one fifth to medium-sized, and the minority to small companies. Most of the responding companies operate globally or within the EU (78.2%).

Table 1. Company demographics (n = 151)

ID	Question	Answers	Total	%
1	Company size	Large (>250 employees)	112	74.2
		Middle (50–250 employees)	30	19.9
		Small (<50 employees)	9	6.0
2	Company branch	Industry	72	47.7
		Transport	39	25.8
		Retail	30	19.9
		other	10	6.6
3	Region of economic activities	Global	75	49.7
		EU	43	28.5
		Austria	29	19.2
		other	4	2.6

We employed distinct statistical techniques to assess our three hypotheses. The first hypothesis (H1) centered on evaluating the prevailing adoption of emissions calculation tools within corporations. Data pertinent to tool adoption were gathered through our survey *(see Appendix: Questions 5, 5a, 5b2)*. We used the chi-square goodness of fit test with a single categorical variable (tool adoption) to assess its distribution across companies. The second hypothesis categorized respondents according to their primary mode of transport *(Appendix: Question 4)*, distinguishing between those who rely solely on road transport *(Group 1, n = 51)* and those who use other modes or combinations of modes *(Group 2, n = 100)*. To detect statistical differences between these groups, we used the Mann-Whitney U test, which is appropriate for comparing independent groups with ordinal or non-normally distributed dependent variables. We coded the groups as ordinal variables *(Group 1 = 1; Group 2 = 2)* for analysis. Hypothesis three involved categorizing responses to an open-ended question *(Appendix: Question 5b1)* aimed at understanding the reasons for limited adoption of emissions monitoring tools. Out of 151 respondents, 82 (54%) were the sample to analyze since they had not yet implemented emissions monitoring. Five categories emerged: planned incorporation of emissions calculation, unplanned incorporation, resource constraints, lack of market demand, and lack of regulatory requirements. Descriptive statistical methods were used to examine the frequency distribution within these response categories.

4 Results

Hypothesis one examined the adoption of emission monitoring tools or methods in Austrian companies. Of the 151 participants, 46% *($n = 69$)* reported using these tools, indicating notable usage but not exceeding the average. A Chi-Square goodness-of-fit test *($\chi^2 = 1.119$, $df = 1$)* assessed whether the adoption rates significantly deviated from chance. The calculated asymptotic significance *($p = 0.290$)* exceeded the defined significance level of 0.05, failing to provide sufficient evidence for hypothesis acceptance. In summary, the data does not support the hypothesis of limited adoption of transportation emissions monitoring tools among Austrian companies. Instead, it suggests a noteworthy presence of these tools in the surveyed organizations. Additionally, we analyzed the current adoption of various emissions calculation tools. Respondents who had not used tools before *($n = 82$)* were presented with a list of different tools [9] to gauge their familiarity. Among this group, the "*Green Logistics"* emissions calculation tool was most familiar *(39%)*. Notably, this response option was followed by the answer "none of these tools are familiar" *(38%)*. Among respondents already using tools *($n = 69$)*, the most common tools were the GHG Protocol *(32%)*, EcoTransIT *(23%)*, and ISO14083 *(22%)*.

Hypothesis two examines the adoption of emissions monitoring tools in relation to the primary mode of transportation used by companies. Among the respondents, the vast majority *(95%)* identified road transport as their primary mode, with 34% *($n = 51$)* relying exclusively on road transport. We performed a Mann-Whitney U test on Group 1, which consisted of these 51 road-only respondents. Of these, 14 had already implemented emission monitoring tools. The statistical analysis shows a notable difference between the two groups. Specifically, the calculated p-value *($p = 0.001$)*, assuming a two-tailed test, is well below the conventional significance threshold of 0.05. This robust statistical evidence confirms a significant difference between the two groups *(73% non-users; 27% users)* regarding the adoption of emissions calculation tools or standards in their corporate frameworks. In summary, Hypothesis 2 is rejected based on the statistically significant finding that companies that rely solely on road transport show a significant reluctance to adopt emissions monitoring tools.

Among the respondents who did not use emissions monitoring tools *($n = 82$)*, we sought to determine the underlying reasons, as posited in Hypothesis three. Most of these respondents articulated that their organization was either in the planning stage or had already begun implementing emissions monitoring (37%). Surprisingly, a significant proportion (38%) admitted that they had no plans to implement such tools. In terms of the specific reasons cited, 13% attributed their decision to a lack of regulatory requirements, 7% to a lack of market demand, and 5% to a lack of internal resources. Consequently, our analysis supports hypothesis H3, as the most common reason for not adopting emissions monitoring tools seems to be the lack of a legal framework.

5 Conclusion and Outlook

In response to the urgent need to reduce GHG emissions in the transport sector, this study offers crucial insights. Our findings reveal a significant uptake of emissions monitoring tools by Austrian companies. However, there is untapped potential, especially among companies relying solely on road transport. This underscores the need for targeted interventions and incentives to encourage tool adoption in this specific segment. Notably, among companies using emissions monitoring, the Global Greenhouse Gas Protocol is the most favored approach. In contrast, non-users are more aware of the Green Logistics tool, but a considerable portion remains unfamiliar with emissions measurement methods. To promote emissions reporting and encourage transparency, policymakers should establish a comprehensive legal framework. Our study indicates that the absence of such a framework is a major barrier to tool adoption. This initial study sheds light on the challenges and opportunities in emissions monitoring in Austrian transport logistics. Future research can delve into case studies and strategies to accelerate the industry's transition toward sustainability and environmental responsibility.

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Appendix

Table 2. Questionnaire

ID	Question	Choice	Answers
1	Company size	single	small, middle, large
2	Company branch	single	Industry, Transport, Retail, Other
3	Region of economic activities	single	global, EU, Austria, other
4	Which modes of transport are mainly used in your company?	multiple	road, rail, air, maritime, inland waterways
5	Are emission monitoring tools in use in your company?	single	yes (proceed with 5a), no (proceed with 5b1 and 5b2)
5a	Which tools are used?	multiple	ISO14083, EN16258, Greenhouse Gas Protocol, GLEC Framework, EcoTransIT, SmartWay, CE Delft, IMO, CCWG, ICAO, IATA, Green Logistics, Green Efforts, ITEC, other [9]

(*continued*)

Table 2. (*continued*)

ID	Question	Choice	Answers
5b1	Why are emission calculation tools not yet in use in your company?	open	text
5b2	Are you familiar with any of the following emission calculation tools?	multiple	ISO14083, EN16258, Greenhouse Gas Protocol, GLEC Framework, EcoTransIT, SmartWay, CE Delft, IMO, CCWG, ICAO, IATA, Green Logistics, Green Efforts, ITEC, none of the above [9]

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Short Review: Optimization Formulations for Enhancing Electric and Hybrid Electric Powertrain Performance

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Abstract. This paper presents a concise review of objective function formulations employed for optimizing the sizing of powertrain components in electric and hybrid electric powertrains, within the scope of the EU-funded Horizon Europe ESCALATE project. The objective is to analyze the techniques used to achieve improved performance and efficiency for powertrains. Efficient utilization of available energy sources, improved range, reduced GHG emissions, and overall system performance are crucial goals. Objective function formulations serve as essential tools for achieving these objectives.

A broad spectrum of optimization techniques is employed in the objective function formulations for electric and hybrid electric vehicles (EVs/HEVs). These include multiple objective functions which simultaneously optimize conflicting/complementary goals, allowing for trade-offs and Pareto-optimal solutions. The review explores the key parameters considered during the optimization process, with a focus on the sizing of electric powertrain components. The goal is to identify the optimal combination of these variables to achieve an optimal powertrain design that maximizes energy efficiency while minimizing cost and environmental impact. Furthermore, the review delves into the challenges and prospects of objective function formulations in the context of electric and hybrid electric powertrains, including the potential to focus on sustainability of designs which has not previously been researched.

Keywords: Optimization · Electric powertrain · Sizing

1 Introduction

The rapid electrification of the automotive industry aims to reduce carbon emissions, but commercial vehicles have lagged behind passenger vehicles. This paper focuses on investigating optimization techniques and powertrain configurations for electric and hybrid commercial vehicles to bridge this gap.

As part of the ESCALATE project, which seeks to design electric trucks capable of long-haul cycles comparable to conventional vehicles, this paper reviews various optimization methods, objective functions, and powertrain designs. The goal is to identify gaps in the current research and explore alternative techniques to enhance range and sustainability.

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The paper begins with an exploration of key powertrain optimization techniques, followed by an overview of different powertrain topologies, and concludes with an analysis of the objective functions used in the optimization process. Final remarks summarize the findings.

2 Optimization Techniques

Metaheuristics are commonly used for powertrain optimization, applying algorithms to complex problems without specific solutions [1]. These algorithms, inspired by Darwin's evolutionary theory, modify populations through recombination and mutation.

A key distinction in optimization approaches is between single and multi-objective optimization. Traditional methods struggle to convert multiple objectives into a single goal, often leading to unrealistic solutions. New methods seek Pareto optimal solutions, where improving one objective worsens others [2].

Genetic Algorithm (GA) optimization mimics natural evolution and is effective for complex, multi-objective problems [2]. A variant, NSGA II [4], is used by [3] to optimize powertrains by balancing the cost of a hybrid energy storage system (HESS) and battery capacity loss. Paper [5] demonstrates GA's use in defining operational strategies for truck fleets to reduce costs. Novel GA methods, like those combined with simulated annealing, offer superior results [6].

Particle Swarm Optimization (PSO), a numerical search algorithm, is another technique gaining popularity for powertrain optimization. Paper [7] uses PSO within a nested co-design framework to optimize plant sizing while the inner loop utilizes a local minimization control problem. Papers [8] and [9] apply PSO to optimize gear ratios, focusing on parametric changes rather than overall topology [8].

Dynamic Programming (DP) is used in power management strategies, considering the optimization over a time horizon [10] for more accurate but computationally expensive results. Paper [11] applies DP to a multi-objective function minimizing cost and energy consumption, but DP's computational growth with increasing variables makes it less suitable for complex projects [12]. Paper [13] notes that DP's need for complete cycle information complicates real-time control.

Nested optimization, employed by [7], involves inner and outer loops for system optimization, with PSO used within these loops. Some papers combine multiple optimization techniques; for instance, [14] compares nested optimization with an iterative approach, finding the latter more efficient, while [15] uses nested loops with different techniques, such as DP for inner loops and GA or PSO for outer loops.

3 Powertrain Topology

3.1 Electric Designs

Research papers that focused on the optimization of powertrains used a variation of configurations with different optimization techniques. In [16] for instance, eight electric powertrain designs were studied for heavy-duty trucks with optimization used to obtain the optimal design. They were divided into two classes: central and distributed drive systems, with varied numbers of electric machines (EM) and transmission units. The optimization aimed to minimize the cost of ownership, finding that the largest reduction was achieved by using a distributed drive over a central drive and a multi-speed gearbox over a single-speed gearbox. The number of electric machines didn't significantly affect the cost of ownership. However, when optimizing for energy consumption only, a higher number of electric machines resulted in the lowest energy consumption and higher powers, as larger EM sizes increased efficiency over the drive cycle.

Some papers tend to focus on one specific topology with minor changes between each project. The standard configuration used by [7] includes a battery, EM, and a gearbox which was varied between single and multi-speed. For long-haul cycles, a multi-speed transmission could reduce EM size by 16% while maintaining performance.

Some papers have changed the number of electric machines. A dual motor can be used to reduce energy costs by optimally distributing the torque between them [10]. On the other hand, the two motors can be used for the front and rear of the vehicle, alternatively [17]. An uneven split between the torque distributions allowed both motors to work in high-efficiency regions, which allows reduces battery size.

A HESS can be used in combination with an electric machine and inverter, one also may use fuel cell technology in combination with the battery and supercapacitors (SC). The first topology has various modes regarding the level of engagement of the battery and SC, based on the required power of the motor [3]. Simulations show that HESS protects the battery more effectively, especially against degradation. The SCs can operate in high current demand allowing the batteries to remain in the low degradation range. SCs are also useful for dynamic power demand when the demand changes rapidly in a narrow window [13].

3.2 Hybrid Designs

Numerous papers on optimization of powertrains looked at hybrid battery electric vehicles (PBEV). Hybrid systems included fuel-cell powered electric trucks, with a focus on regenerative braking as the main use for the battery [18]. Some papers looked at the combination of battery and an ICE as a range extender [19]. These papers were also useful for the type of optimization with less focus on the configuration of the electric powertrain.

4 Objective Function Formulations

4.1 Energy Consumption Formulations

Paper [7] minimizes the average battery energy consumption over the drive cycle. The calculation is identical to the method used in authors' following paper [16]. Paper [9] uses a similar approach to minimizing energy consumption, however the integral of power is broken into time spent within each gear stage, as well as incorporating shifting time. For papers which look at HESS, both the battery and supercapacitor have to be considered in the objective function. Paper [11] has a similar objective function in regard to minimizing energy consumption, however the energy of the supercapacitor is included in the function. Paper [3] reduces the capacity loss of the battery over its lifetime, rather than optimize energy consumption, which are directly correlated.

4.2 Cost Formulations

Research papers focused on minimizing costs typically calculate both capital and operational costs. Capital cost covers component expenses, while operational cost refers to energy use during the vehicle's lifecycle. Paper [11] expands on this by including replacement costs, calculating battery capacity loss, and replacing batteries when the loss exceeds 20%. They also introduce a capital recovery factor (CFR) to account for interest rates. Paper [20] considers capital and operating expenses, pricing the EM and inverter per kW of power and factoring in future battery price reductions. Paper [16] links energy consumption during a drive cycle to operational costs, using the integral of battery power to optimize energy use. Maintenance costs, including repairs, are addressed by [18], calculated per km. Similarly, paper [17] calculates operational cost by the change in battery energy from start to end of the cycle. Table 1 portrays the equations used in the papers referred to in this section highlighting the variation of equations used to achieve the optimal design of a powertrain. This is perhaps the most essential part of optimizing powertrains as an objective function must be formulated correctly to allow the optimization to converge successfully and give an accurate pareto line.

Table 1. Various objective function formulation used in optimization papers

Reference	Formulation
[17]	$cost = cost_{op} + cost_{comp}$
[3]	$\{(f_1(x_1) = cost_{SC}(x_1)\&f_2(x_1, x_2) = Q_{loss_{Bat}}(x_1, x_2))\}$ $x_1 = [M_{SC}, N_{SC}], x_2 = [M_{Bat}, N_{Bat}],$
[11]	$\min_{\overrightarrow{x}} J = [J_E, J_C]$ $minJ_E(\overrightarrow{x}) = \sum_{i=1}^{T-1}(E_{BT}(K) + E_{SC}(K) + E_{BT}(K+1) + E_{SC}(K+1)$ $J_C(\overrightarrow{x}) = cost_{Cap}/360 + cost_{op} + cost_{rep}/360$
[20]	$pTCO = pCAPEX + pOPEX$
[18]	rco $= cost_{inv} + cost_{pv\_energy} + cost_{pv\_maint} + cost_{pv\_batt\_replace} - cost_{residual}$
[7]	$J_C(x_g(t)\|E_b, P_M, r_g, \Lambda(t))$ J $= \overline{E_S} = \frac{1}{D_C}\int_{T_o}^{T_f} P_s(t)dt$
[16]	$CTO = C_E + C_V$

4.3 Sustainability Formulations

Sustainability is crucial in engineering designs and should be a key focus in optimizing electric and hybrid powertrains. While research on electric trucks covers charging infrastructure and emissions related to the electricity grid, optimization should prioritize sustainability, not just cost. Most optimization papers overlook GHG emissions and environmental impact, highlighting a significant gap in research on electric and hybrid commercial vehicles.

5 Concluding Remarks

The paper reviews key research on optimizing electric and hybrid powertrains, highlighting variations in optimization techniques, topologies, and objective functions. Despite advances, gaps remain that could further enhance powertrain performance.

The research covers various configurations, including transmissions, multiple EMs, and HESS, but overlooks combining HESS with transmission modelling. Papers like [12] and [3] focus on HESS but stop at the motor, ignoring the transmission. Integrating transmission and gear ratio optimization with HESS could yield better results. Additionally, sustainability, apart from some about environmental emissions, has been largely ignored in these studies.

Overall, powertrain optimization has improved the design and performance of electric and hybrid trucks, with notable gains in range, cost, and performance. However, further research could help commercial vehicles reach development levels similar to passenger vehicles.

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International Collaboration in the Area of Road-Transport Research: FUTURE-HORIZON Key Findings

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Abstract. The paper delivers insights from the EU-funded FUTURE-HORIZON project, which systematically explored strategic international collaboration opportunities (INCO) in road transport research (RTR) between the European Union and global partners, the focus is on achieving long-term sustainability and optimizing collaboration efforts. In the form of country-specific fact sheets, the project showcased key stakeholders and research domains within established markets the paper offers insights into the main challenges and opportunities in the road transport sector and provides recommendations for systematic approach to identifying collaboration opportunities. A central feature of the reported work is an innovative SWOT analysis aiming at identifying both opportunities and threats for potential collaboration between the European Union and other nations in RTR. Covering the areas of the European Road Transport Research Advisory Council (ERTRAC) Energy & Environment, Electrification, Urban Mobility, Freight & Logistics, Road Safety, and Cooperative, Connected and Automated Mobility, the analysis flips the logic of a traditional SWOT analysis by assessing opportunities and threats of collaboration caused by strengths and weaknesses of each country from an EU perspective and for specific examples. This paper shares select outcomes from international initiatives aiming to implement novel mobility solutions for demonstration and replication in partner cities around the world. Solutions span a range of innovative actions, including sharing systems, public transport, and city logistics, as well as energy and infrastructure requirements. This paper serves as an essential guide for dialogues on international collaboration in road transport research and offers direction for partnerships with both advanced and emerging economies.

Keywords: International · collaboration · sustainable · road · transport · research

1 Introduction

The European Union, in the past, adopted a rather open stance towards international collaboration on research and innovation based on three core objectives: Enhancing the Union's excellence and attractiveness in research and innovation, while boosting

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its economic and industrial competitiveness, addressing global societal challenges, and supporting the Union's external policies. However, in light of recent multiple global developments and crises where human rights and freedom, the earth's climate and environment as well as fair economic and societal developments were put at risk, the EU has adjusted its approach. Particularly, recognizing that certain countries started to aim for technological dominance using discriminatory measures and apply research and innovation for global influence and social control, for the current research framework, Horizon Europe, the EU is adopting a more strategic policy. While still emphasizing reciprocal openness in research and cooperation, the Union also aims to support the goals of open strategic autonomy and adjust its cooperation accordingly.

This paradigm shift also affects international collaboration in road transport research (RTR). Topics like road safety, air quality, and climate action demand global solutions. To effectively address these challenges, it is vital to understand the research objectives, tools, and ecosystems of potential partner countries. Assessing their strengths and weaknesses and driving conclusions on the related opportunities and challenges for potential collaborations from the EU's standpoint is crucial. Especially engaging key stakeholders from the European road transport research community is essential to maximize benefits for Europe's global competitiveness and sovereignty, and though a systematic, evidence-based, and traceable strategy ensure unbiased and factual advice. Furthermore, it's crucial to articulate the reasons for pursuing international collaboration, especially when it results in mutual benefits. Following this rationale, the Coordination and Support Action FUTURE HORIZON, funded under the Horizon 2020 framework program, implemented a structured analytical pathway consisting of a global overview of RTR strategies, a comparison with the EU, a comprehensive assessment from the perspective of industrial innovation, an exemplary study of international cooperation efforts, and a set of recommendations for the future. The analysis covered primarily the US, China, South Korea and Japan, while also considering outstanding developments from emerging economies. It is summarized step-by step as follows.

2 Global Overview of Road-Transport Research Strategies

To enhance the strategic planning of Europe's robust RTR ecosystem, the FUTURE HORIZON project initiated a comprehensive analysis, benchmarking, and collaboration with other major global regions. The initial step was the creation of a database. This information hub was then validated and enriched with insights from regional "ambassadors." Country-specific factsheets were produced, focusing on four key regions: the US, China, South Korea, and Japan. Each factsheet addresses the six core themes of the ERTRAC roadmaps: a) Energy & Environment. b) Electrification, c) Automation & Connectivity, d) Urban Mobility, e) Freight & Logistic, and f) Road Safety.

For each theme, the factsheets highlight the specific country's policies, programs, and notable RTR initiatives. They also feature a map showcasing major contributors from academia, industry, and policymaking. Additionally, the factsheets provide an overview of relevant socio-economic trends, the impact of COVID, and an initial assessment of the strengths and weaknesses of each region's RTR ecosystem. The most recent versions of these factsheets are available to the public (Future Horizon 2022a).

3 Comparison of RTR Strategies: EU vs. Other Established Markets

Utilizing the factsheets, 24 key examples (four examples for each of the core themes) highlighting potential opportunities and challenges for research collaboration between the EU and other countries were identified. These examples span each combination of country and ERTRAC roadmap topics. For each of these 24 examples, paired with an overarching analysis of the country's RTR landscape, a detailed, converted SWOT analysis was conducted. This way of analysis was specifically adapted to the research question of interest in FUTURE HORIZON. It displayed the strengths and weaknesses of each country within the specific thematic field and assessed the potential benefits and risks of collaboration with the EU, considering both strengths and weaknesses, and led to 96 unique analyses. Each one pinpointed the ideal collaboration level, which varies in four degrees, from a simple knowledge exchange to the pursuit of strategic sovereignty. To distil the findings, a two-axis indicator chart was created for each ERTRAC topic and places each country on a horizontal spectrum (from threats to opportunities for collaboration) and a vertical spectrum (from the EU's recommended response, from strategic autonomy to openness). In addition, these findings were supplemented with specific lists highlighting (i) specific topics where collaboration offers country-specific benefits to the EU, topics where collaboration poses potential threats to the EU, and (iii) general areas of international collaboration within the given thematic fields, e. g. here for electric mobility. Topics with benefits for EU:

- Strategies towards end-to-end battery value chain & recycling/2nd use with U.S.,
- Role of PPPs for research and innovation for EVs, wireless charging with Japan,
- Energy-efficient electric vehicle and battery value chain creation through state driven coordination with China, and
- Holistic implementation of adaptable electric vehicle platform with South Korea

Topics with risks of collaboration for Europe:

- Environmental standards for batteries might affect European values, ethics and design principles,
- Threat of a market dominance by battery and EV industry, and
- Competition by new entrants into the value chain, e. g. from energy or IT sector regrading smart charging.

Topics of global relevance for R&I collaboration:

- Interoperability of charging systems,
- New charging technologies (fast charging, inductive charging)
- Resource efficiency & circularity of batteries/EVs

Further details including all SWOT analyses, the indicator maps and the list of collaboration topics may be derived from the dedicated project report (Future Horizon 2022b). It is important to note that many of the paradigmatic examples considered for this analysis were also identified from the ERTRAC working group leaders, making the analysis particularly rich.

4 Comprehensive, Systematic Approach

The next step in developing fact-based recommendations for international collaboration is establishing a methodology that gives the ERTRAC Working Groups a structured approach to work with the new information and starting with the roadmaps for each of the core themes and research priorities that have already been pre-identified as potential areas of action for international collaboration by the experts involved. If not already included in the extraction of research priorities from the roadmaps, the experts consult the international fact sheets that will provide possible impulses and inspiration to update the list of research priorities. Once this list is completed, an essential step is to consult the SWOT analysis with each of the identified research topics and assess the suitability of that topic for International Collaboration. Ideally the specific research priority topics are input for evaluation using the converted SWOT analysis approach. However, if the research priority topic has not yet been directly evaluated in the converted SWOT analysis, then it is possible to reference similar analyses. Once a topic has been identified as a potential recommendation of international collaboration the format needs to be specified. Overall, the general formats of collaboration in INCO projects can be divided into the following categories:

- Exchanging information and documentation,
- Coordinating studies, programs, and activities,
- Conducting joint activities:
- Collaborative projects and coordination activities, funded by the different countries involved, joint calls and synchronized calls,
- Joint analyses, evaluations, and other collaborative activities, including joint international workshops or meetings, short-term visits by researchers, sharing of material, data, and information, coordination of sampling or analyses, and joint publications,
- Participating in working groups.

The final step in the methodology is to assess the degree of mutual benefit based on the selected form. If the potential for mutual benefit is high, then the format pre-selected for collaboration remains, but would be intensified. Otherwise the degree of collaboration can be varied from “provide knowledge and develop collaboration” to “Gain knowledge and competence through collaboration”, Fig. 1, depending on the assessment and reflecting on discussions carried out in the converted SWOT analysis.

A sovereignty strategy to build up technology or know-how would be recommended if either the INCO would not be suitable, or the mutual benefit assessed to be low. This two-decision gate approach ensures recommendations are traceable, fact-based and have a high potential to create a collaboration with mutual benefit.

5 International Cooperation with Emerging Economies

The systemic approach on international collaboration opportunity mapping also included an assessment of developing economies in Africa, Asia, and Latin America to provide a more complete picture of the collaboration extent. Building on on-going international

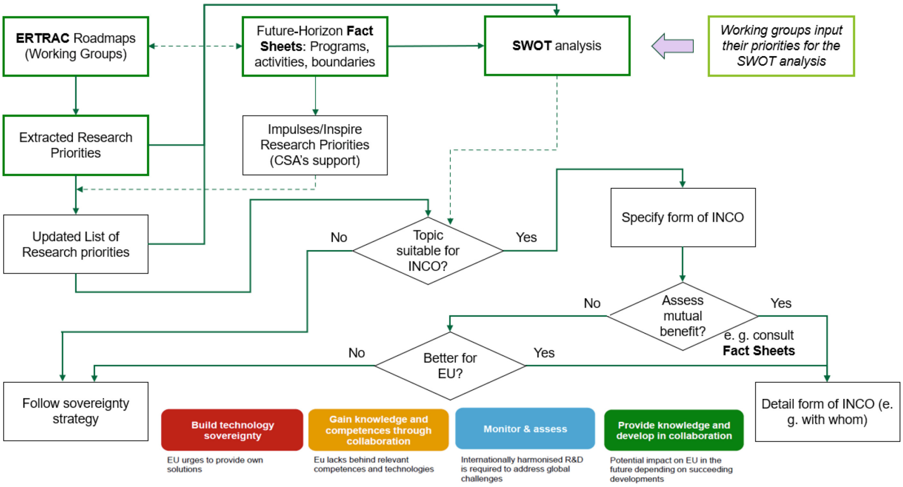

Fig. 1. Flow chart for the systematic approach

cooperation projects such as SOLUTIONSplus and e-BRT-2030 opportunities for international cooperation with developing and emerging economies showed that key potentials with mutual benefit can be found in areas such as electric first/last-mile connectivity solutions for passenger and freight transport, electric mini-buses and cargo-vans and electric Bus Rapid Transit systems. Specific formats for such collaboration to integrate these in a wider perspective with urban planning, renewable energy, local grids, battery evolution, and charging infrastructure and contribute to a closer coordination among research & innovation, development cooperation and climate action programs are identified:

- Living Lab Projects: Co-development of e-mobility solutions for passenger and freight transport urban and rural operating environments.
- Peer-exchange on Mobility Solutions: Knowledge sharing among peers from local and national authorities, academics and provide sector actors from Africa, Europe, Asia and the Americas.
- Ecosystem Creation: An umbrella of transformative change, efficient implementation blueprints, and a synchronization of both local and international stakeholders.
- Working Groups & Innovation Hubs: Platforms to synergize research, funding, and create partnerships. Synchronizing research & innovation projects with scale-up implementation projects to foster impact and longer-term collaboration.
- Fostering Local Value Chains: Targeted collaboration between industry and local entrepreneurs to help create mutual benefits, fostering the decarbonization goals.

These collaboration formats are intended to contribute to an ecosystem of electric mobility startups and public transport operators, pave the way for broader regional adoption, market development and provide opportunities for co-development of tailored products and services between European and international actors (see SOLUTIONSplus 2022).

6 Summary and Outlook

This paper serves as reference for discussions on international collaboration in the RTR sector and provides an orientation, fact-based and traceable, for international cooperation with established and emerging economies. The systematic development of these concepts is aligned with ERTRAC's recommendations for innovation deployment towards a sustainable and competitive road transport system in Europe and beyond. These always need to be considered/integrated in a wider perspective with urban planning, renewable energy, local energy supply grids, battery evolution, and charging infrastructure and contribute to a closer coordination among research & innovation, development cooperation and climate action programs. Closer collaboration depends on mutual benefit and projects will emphasize participatory processes, encapsulating governance, financial structures, and regulations, to serve templates for other organizations/regions.

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Promoting Sustainability Through e-vehicle Procurement: Experiences from Three Continents

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Abstract. By favouring innovative solutions that serve sustainability goals, sustainable procurement can aid in mitigating the negative externalities of mobility. However, a deeper understanding of the sustainable mobility procurement processes, and the potential pitfalls and best practices in the global scale is still lacking. To address this shortcoming, we conducted a qualitative study on e-vehicle procurement, drawing on interview and survey responses of procurers involved in a project aiming to promote urban electric mobility in various urban areas across the globe (EU SolutionsPlus project). Based on the responses, sustainability strategies and goals are widely adopted in cities across the globe, while differences arise in how these strategies are incorporated into regulatory frameworks and procurement guidelines. The results suggest that having flexibility in the procurement process supports collaboration with the suppliers, and the acquisition of suitable solutions for the given context.

Keywords: Sustainable procurement · e-vehicles · urban mobility

1 Introduction

Mobility and transportation contribute to various negative impacts that threaten the sustainability of our communities. Notably, these systems account for 23% of global CO2 emissions, while also causing local environmental issues in many areas [1]. To address these problems, both public and private entities are facing increasing pressure to mitigate the environmental and other sustainability concerns associated with mobility and transportation.

A prominent approach for mitigating negative externalities of mobility is sustainable procurement [2]. By considering and evaluating the environmental impacts of mobility solutions, and favouring innovative solutions that align with sustainability goals, sustainable procurement can significantly contribute to reducing emissions from mobility [3, 4]. Furthermore, beyond its direct effects, sustainable procurement acts as a catalyst for market direction, fostering innovation, development, and uptake of environmentally friendly mobility options.

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However, several hurdles hinder successfully employing sustainable procurement, including lack of knowledge, insufficient commitment within organizations, and a perceived conflict between costs and sustainability [5]. Despite these challenges being well-known, a detailed understanding of the sustainable mobility procurement processes, and the potential pitfalls and best practices that enable successful sustainable procurement in the mobility domain is lacking. These limitations impede our understanding of procurement practices globally and hinder future efforts to bring sustainable procurement to the forefront as a worldwide means to tackle the global sustainability issues we face.

To address the shortcomings of the extant corpus, we conducted a qualitative study focused promoting sustainability through e-vehicle procurement. To do so, we gathered insights from interviews and qualitative surveys with procurers involved in the EU SolutionsPlus project [6], which aims to promote urban electric mobility in Africa, Asia, Europe and Latin America. Based on the data, we elaborate on the various procurement practices and procurer experiences in cities across the globe. Moreover, we identify potential challenges, pitfalls, and best practices in sustainable mobility procurement, with a specific focus on e-mobility.

2 Methods

During April-May 2023, stakeholders involved in the e-mobility procurements associated with the SOLUTIONSplus project took part in the study. The respondents were involved in procurements in the cities of Hamburg, Hanoi, Kathmandu, Pasig and Quito. The data was collected through a survey that included open-ended questions covering procurement goals and strategies, requirements, costs, actors, knowledge, and information as well as challenges and best practice. The survey was distributed to the respondents via email, offering them the choice to complete it independently and email their responses to the researchers or to be interviewed using the same set of questions as in the survey. Altogether 5 respondents representing 5 different organizations participated in the study. A total of 4 participants provided written survey responses, and one participant was interviewed. We used thematic analysis to identify relevant patterns that serve the research objective.

3 Results

We identified patterns and differences in relation to strategies, regulation and guidelines governing the procurement, the procurement practices and processes carried out, and how the collaboration as well as exchange of information was facilitated throughout the process in different cities.

3.1 Strategies, Regulation, and Guidelines

All respondents acknowledged the existence of sustainability goals, strategies, and plans guiding the procurement, while differences emerged in how these were incorporated into regulations and guidelines. Three of the respondents acknowledged specific regulations and guidelines governing the procurement processes that were established by national, local, or organizational authorities, and varied depending on the sustainability aspects of procurement they emphasized. For example, in Quito, where electric cargo bicycles were purchased, the respondent mentioned that the procurement followed regulations instantiated by a municipal institution, whose main purpose is to prevent corruption in procurement as well as the National Public Procurement Service, and the Ordinance of the non-waste of resources, that promote purchases that are responsible in social, economic, and environmental terms.

One of the respondents (Hanoi), however, did not acknowledge regulations or guidelines to promote sustainable procurement. Despite the lack of formal guidelines, the respondent perceived that there was a consensus among procuring authorities, possibly stemming from the overarching sustainability goals and strategies, to favour environmentally sustainable options, as well as flexibility that allowed considering the sustainability aspects in the procurement process: "As *far as we know, there is no specific policy on promoting greenness in procurement. However, in the general legal provisions, there is still openness for the prioritized contents when making procurement such as priority for domestically produced goods, goods / technologies with environmental protection."*

Generally, while existing regulation and guidelines were seen to promote transparency, in some cases they were considered as restrictive, as noted by the Quito respondent when asked about the challenges faced during the process: *"Bureaucracy in the process for the development and follow-up of the implementation of the project. The Environmental Fund must comply with the regulations established in the Guide for the administration of agreements in the Municipality of Quito that can be very rigid and restrictive."*

3.2 Processes and Practices

While regulation and guidelines generally set boundaries to the procurement processes, their inherent flexibility often allowed procurers to use their judgement in how the procurement processes were carried out. Many respondents highlighted the importance of planning and setting the direction early in the process in eventually enabling a successful procurement. Although planning early on was seen as a critical stage, it was deemed important to maintain flexibility to alter and refine the plans in the later stages of the procurement. As mentioned by the respondent from Hamburg, where the procurement considered utilizing e-scooters as first and last mile solutions to complement public transport, striking a balance between early-on planning, and having the flexibility to later utilize the expertise of the suppliers was deemed challenging: "*One of the main challenges during the procurement process was - at the beginning - to describe our e-scooter service as concretely as possible without making any restrictions. Our ideas had to be formulated precisely although we still wanted to define some aspects together with the provider we are searching for."*

Requirement and criteria setting was seen as a critical stage in the procurement process, and many of the respondents emphasized that sufficient effort should be dedicated to successfully set the requirements in detail as this would aid in the following stages of the procurement process. In the case of Hamburg, the procurers went beyond relying solely on the processes and knowledge within their organization to set the requirements and selection criteria, tapping into the domain expertise of potential service providers. The Hamburg procuring organization initially devised a comprehensive set of selection criteria jointly with innovation, procurement, sales, and safety departments. However, during the tender call stage of the procurement process, these criteria and requirements were discussed and refined collaboratively with the businesses that responded to their call. While giving the service providers space to affect how the developed service would turn out to be was deemed a good practice, it also posed a challenge in terms of balancing the setting of specific requirements that address the procuring organizations' needs and giving the service providers freedom to ideate innovative solutions.

However, in some countries and locations e-vehicle technologies are novel and less established, which caused hindrances to the procurement process. In Kathmandu, where the procurement considered the conversion of a diesel bus into a e-bus, the lack of potential supplier expertise was considered as the main challenge throughout the procurement that also increased the length of the process. A similar lack of local suppliers was observed in Quito where the e-cargo bicycles were procured, posing one of the main challenges faced by the procurers. Additionally, problems arose due to unforeseen changes in market and policy environments during the process, as mentioned by the Hanoi respondent: "*The main difficulty in the procurement process is the change in policy, the change of market / unit price between the project preparation stage and the procurement implementation stage.*"

3.3 Collaboration and Information Exchange with the Suppliers

Ensuring the efficient flow of information between the procurers and suppliers was highlighted by many of the responses. Particularly, efficiently communicating the requirements and ensuring that suppliers comply with them was deemed challenging, while the means for tackling these issues included detailed procurement documentation and regular check-ups. However, some respondents highlighted the importance of a two-way information exchange that was enabled by the flexibility in formal procurement regulations and guidelines, as well as the flexibility instantiated when planning the procurement activities. In the case of Hamburg, the procuring organization and the service provider engaged in continuous dialogue of the future service, which was considered an important success factor throughout the process. This information exchange was utilized in the business area identification phase, where the procuring organization and the service provider would discuss their ideas regarding the novel service. In the latter stages of the procurement, the two organization members arranged regular meetings, some of which took place outside in the project environment, where the focus was on the spatial issues that needed consideration before the implementation, such as parking spaces, and markings: "*We visited the stations. We discussed where we should position the physical parking zones. We had discussions at the end every week. We came closer and closer to the final concept and then we could, for example, book more or less parking spaces, we could buy the parking signs and order the pavement markings. This was a step-by-step approach. Very good, very useful discussions.*" A similar emphasis on the importance of the dialogue between the procuring organization and the provider was observed in Quito. According to the respondent, the public procurement processes that are normally followed do not allow sufficient dialogue between the providers and the procurer. However, in the case of SolutionsPlus, the procurement was conducted through a Competitive Fund, and therefore the process allowed more flexibility to tailor the procured vehicles according to what is convenient for the provider and the procurer: *"…it provides greater openness to dialogue with the manufacturer to make changes to the design, vehicle components, and in general adjusts to the reality of the manufacturer and the financier's needs without imposing difficult and bureaucratic procedures from public purchases."*

4 Discussion

Based on the results, goals, and strategies to promote sustainable mobility are widely adopted in across the globe and sustainable procurement is considered as one potential instrument for that. However, notable variations exist in how strategies and related procurements are put into practice. One of the major differences observed among the cities relate to regulations and guidelines governing the procurement. In certain cities, procurement activities were strictly regulated, while the absence of stringent regulations promoting sustainability in procurement was evident in others. Although the lack of strict guidelines implies that sustainability considerations are addressed in a non-systematic manner, governance deficiencies can create opportunities for innovative solutions and experimentation. This flexibility may give rise to organic developments that contribute to the sustainable development of urban areas. While formal regulations provide structure and uniformity for procurement processes, the absence of rigid guidelines can foster an environment where creative approaches and unconventional ideas are explored [7]. This aspect was highlighted in the responses, where rigid procedures were seen as a hindrance to establishing dialogue with the suppliers to foster innovation and find the optimal e-mobility solution for the context. Overall, our findings suggest that successful and fluent e-mobility procurement is enabled by flexibility in existing formal regulations and guidelines as well as in maintaining this flexibility when planning the procurement to ensure the capacity to adapt to changing policies, markets, and technological advances in e-mobility.

In the light of our analysis, procurers should balance the procurement criteria to allow flexibility while providing sufficient details. Based on the responses, formulating detailed and clear procurement criteria is essential as it will aid the suppliers in the bidding phase and improve the fluency of the remaining phases of the procurement. However, posing too many constraints in criteria setting may come at the cost of purchasing suboptimal solutions for the given context. E-mobility technologies are advancing rapidly, and are additionally often accompanied by novel service models, such as those based on sharing economy, which means that they are still less established in many regions and procurers often have only limited experience with and competence on them. Therefore, providing too many constraints by criteria setting might hinder the provider from proposing a solution that is suitable for the use context and optimal given the current state of e-mobility technologies. Moreover, based on the responses, establishing market dialogue, and involving providers in the criteria formulation seems to be a good practice given the novelty of many e-mobility technologies and service models.

Additionally, procurers should find means to diversify their expertise. As noted previously, procurers in many regions may still have limited experience with e-mobility due to the novelty of these technologies. Means to overcome this lack of expertise include the use of procurement consultants, or the utilization of the expertise of the different departments in the case of large organizations. However, procurers can also strive to leverage the expertise of the providers throughout the process to refine their business models and products by implementing practices that enable incremental co-development together with the providers.

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DCFC Strategies for Automotive Li-ion Cells: Non Disruptive Electrochemical Analysis and Post-mortem Raman Characterization

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Abstract. The shift towards E-mobility transportation represents an important step to guarantee an ecological and energetic transition. To have a good market penetration of electric vehicles, however, we must consider the needs of consumers, who demand short charging times and a long battery life. The study and design of DCFC (direct current fast charging) profiles is fundamental to achieve this goal. In a previous work, new DCFC profiles based on Multi Stage Constant Current (MSCC) charge step were proposed. The new profiles have been designed with the aim of providing a fast charge that avoids the conditions in which the cell incurs in lithium plating. In this work the results of two characterization techniques are presented: Electrochemical Impedance and Raman Spectroscopies. The first confirms the advantage of using the customized profiles, without dismantling the cell, while the second confirms the absence of Li plating on the anode surface, after the teardown.

Keywords: Li plating · Fast Charging · Li ion cell aging · Raman Spectroscopy · Electrochemical Impedance Spectroscopy

1 Introduction

Since European governments are pushing automotive companies to switch from internal combustion engine (ICE) vehicles to battery electric vehicles (BEV) to answer the more and more urgent need of decarbonization, it is crucial to adopt strategies for ensuring a production and use robust and cost efficient [1]. Since a significant amount of cells

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will be needed within the next years, it is fundamental to adopt a winning strategy to handle these products properly, maximizing performances, guaranteeing safety and prolonging the cycle life. The implementation of optimized fast-charging profiles can be helpful to decrease the time needed for a complete charge, without degrading the cell performances and prolonging the cycle life of the battery pack [2]. In a previous work, two methodologies were used to collect information about the current/voltage limits needed to design custom charging profiles, following the so-called Multi Stage Constant Current (MSCC) method, as previously described in [3]. Based on the data matrix collected, four new DCFC protocols were designed and compared to the current Reference charge procedure: a double step standard profile. Figure 1 shows the DCFC profiles reported as C-Rate vs Time (Fig. 1A) and Voltage vs Capacity (Fig. 1B).

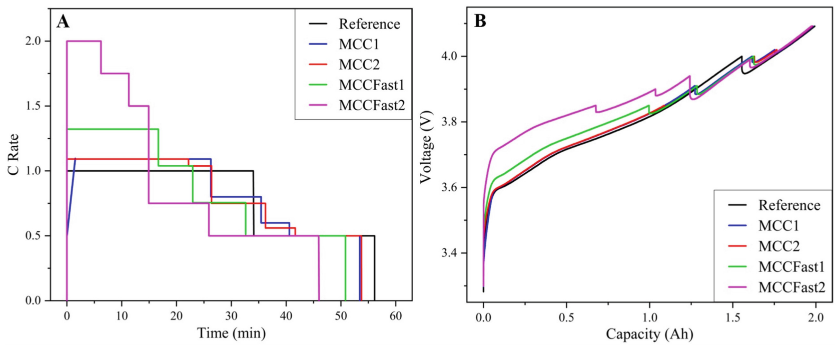

Fig. 1. (A) C-Rate vs Time charging profiles and (B) Voltage response vs Capacity charging profiles.

The tailored charging profiles were applied to a batch of cylindrical cells for a prolonged cycle aging test: 1000 cycles with 1C discharge were performed. To evaluate the new DCFC protocols in comparison to the Reference profile, a deepened characterization study was performed on the aged cells. Physical-chemical (SEM, XRD, Particle Size Analysis, ICP) and electrochemical (Incremental Capacity Analysis, Internal Resistance Measurements) analysis were reported in previous works [4, 5]. Lithium plating was observed by visual inspection of anode electrodes in regions characterized by high curvature (typically the inner part of the jelly roll) only for cells that aged with Reference and MCCFast2 samples. It was not possible to determine the presence of lithium plating in the remaining part of the electrodes.

In this work the new results of two additional techniques, the Electrochemical Impedance Spectroscopy (EIS) and the Raman Spectroscopy, are presented. EIS was used to monitor the internal resistance of the cell, while Raman spectroscopy was used to detect the onset of the lithium plating phenomenon, where invisible at the visual inspection.

2 Experimental Results

2.1 Electrochemical Impedance Spectroscopy (EIS)

During the aging of the cell significant changes in the internal resistance of the system can occur due to the degradation of both electrodes and electrolyte. Electrochemical Impedance Spectroscopy (EIS) measures the resistance of the battery cell as a function of frequency: fitting EIS spectra useful information about cell internal resistance can be obtained [6]. It's important to find the most appropriate equivalent circuit for the fitting procedure, which depends on the experiment conditions and on the specific features of the cell studied. In this case, the EIS data of the five cells cycled with different DCFC protocols were fitted by using a very common equivalent circuit, already published in literature, described in Fig. 2 [7]. In the circuit, R (Resistance) represents electron transfer across an interface, CPE (Constant Phase Element = an non-ideal capacitor) represents non-faradaic charging at an interface and W (Warburg Impedance) represents the diffusion of ions that causes the 45° slope diagonal line in the Nyquist plot.

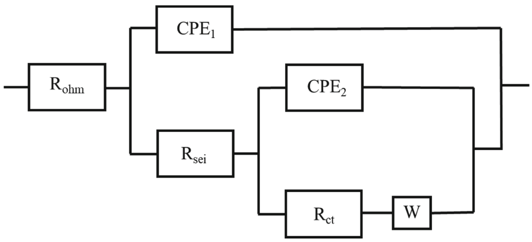

Fig. 2. Equivalent circuit for EIS fitting.

Figure 3 reports the fitting of the EIS spectra of the aged cells and the calculated values of R_{ohm}, R_{SEI} and R_{CT} for the different cells: after 1000 cycles the charging protocols caused different aging on the cells. R_{ohm} is indicative of the electrolyte resistance: MCC2 shows the best performances, while MCCFast1 and MCC1 cells present an electrolyte resistance intermediate between MCC2 and Reference sample, confirming the SoH% trend observed after 1000 cycles [3]. As expected, the tailoring of the charging strategy influences positively the aging behaviour, enhancing and prolonging the cycle life. The total interfacial resistance from the solid electrolyte interphase (R_{SEI}) and the charge transfer resistance (R_{CT}) are represented by the two semicircles (overlapped in Fig. 3) at high and medium frequency ranges. MCC1 and MCC2 present the best SEI conditions, confirming to be valid alternatives to replace Reference protocol.

R_{CT}, also visible at medium frequencies, is correlated with the material loss: lithium loss, structural/mechanical degradation and chemical dissolution/decomposition can be translated into an increase of R_{CT}, generating a worsening of the cell conductivity. Figure 3 shows that all charging protocols perform in a very similar manner, with values of R_{CT} between 5 and 7 mOhm, for the worst cases.

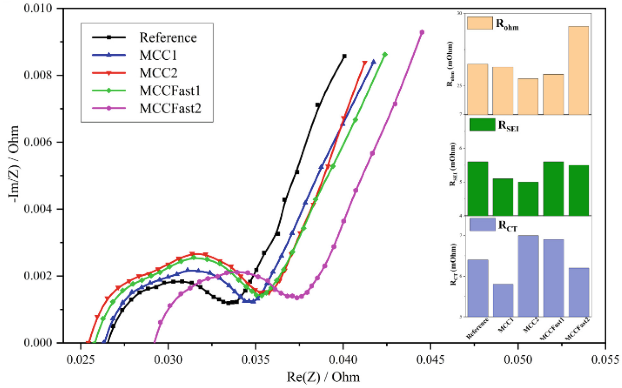

Fig. 3. EIS Nyquist plots responses and values of R_{ohm}, R_{SEI} and R_{CT} for the different cells.

2.2 Raman Spectroscopy

Since fast charging is very critical for the anode, due to the formation of Li plating, it is important to pay attention to its formation. Raman spectroscopy is a useful technique for the detection of lithium on the surface of electrodes, if invisible at the visual inspection. Li plating can be detected by analyzing the Raman vibrational spectra: the presence of lithium on the surface changes the vibrational modes, differentiating the lithium plated surface from the non-plated one. Figure 4 shows the Raman spectra obtained on the different anode samples.

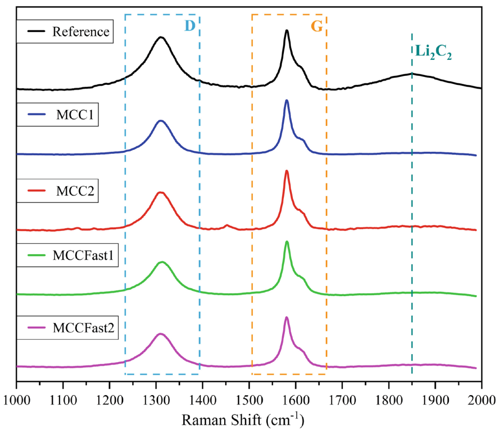

Fig. 4. The Raman spectra obtained on the different anode samples.

The band at ~1847 cm^{-1} can be used as a marker for Li plating evidence since it is attributed to acetylide groups (−C≡C −), occurring in electrochemically plated lithium, forming Li_2C_2 [8]. In Fig. 4 it is possible to notice that no peaks related to Li_2C_2 are present for the samples associated to the custom charging protocols, symptoms of no

Li plating, while the Reference sample presents a very broad and low intensity peak, related to some irreversible Li plating presence. Considering the 1100–1700 cm^{-1} range, there are two peaks typical of graphitic materials: the G band and the D band. The G band, located at 1580 cm^{-1}, corresponds to the plane C-C stretching (E_{2g}), while the D band, located at 1350 cm^{-1}, corresponds to the breathing mode (A_{1g}), that describes non graphite carbon linked to defects and grain boundaries. Calculating the ratio between I_D and I_G it is possible to measure the entity of degradation of the crystal structure: the higher is the ratio I_D/I_G, the greater will be the degradation of the sample [9, 10]. In Table 1 the calculated ratios for the different samples are reported: Reference anode presents the highest ratio, presenting the worst conditions in terms of crystalline structure retention, appearing as the most degraded.

Table 1. I_D/I_G ratios for each sample.

Sample	I_D/I_G
BOL	0.19
Reference	0.87
MCC1	0.61
MCC2	0.64
MCCFast1	0.62
MCCFast2	0.68

With the Raman microscope a map of spectra for each sample were recorded (Fig. 5), analyzing areas with lower crystallinity (blue areas) and others with higher crystallinity

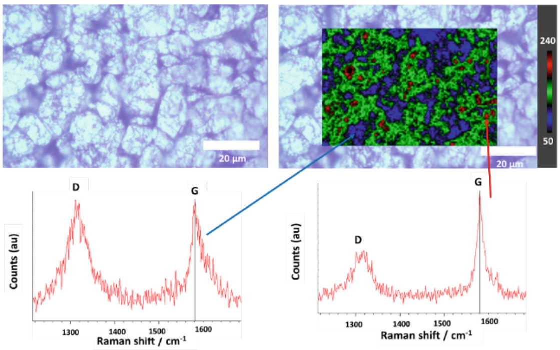

Fig. 5. Methodology for chemical mapping of a 60x40 µm area of anode electrode. 12.000 spectra are obtained and the color area corresponds to the peak intensity of the 1580 cm^{-1} graphite peak (G) of the anode; red dots correspond to regions with higher graphite structure, while blue regions exhibit higher the diamond (D) carbon structure. The figure was created by the software Wire 5.3, Renishaw plc, Gloucestershire, GL12 8JR, UK processing data of the micro-Raman Qontor Renishaw Instrument. Source: Authors.

(red areas). In this way, representative curves are reported, obtained from the average of the various samples in several zones of the same type.

3 Conclusion

The present work shows data obtained from an extensive cycle aging campaign, followed by a multi-technique characterization activity, previously described [3, 4]. Here, both non-destructive and destructive methodologies are proposed.

The main outcomes of our research can be summarized as follows:

- EIS is a useful tool for the monitoring of full cell ageing during accelerated ageing protocols including fast charge profiles.
- From non-destructive EIS analysis it was possible to gain insight into the general trend of the ageing of the cell and to obtain information on the main ageing phenomena related to Ohmic losses, charge transfer limitations and SEI growth. On the other hand, the technique is not sensitive to lithium plating and for this reason we adopted Raman spectroscopy.
- Raman spectroscopy was able to exclude the onset of lithium plating on the anode electrodes where invisible at the visual inspection (except for the reference sample, where a signal related to Li_2C_2 is observed).
- New perspectives for Raman spectroscopy are related to the extension of our methodology to analyse different anode formulations and to the analysis of cathodic materials.
- Regarding the non-destructive approach, the implementation of dynamic EIS during the charging step could be useful to highlight the occurrence of lithium plating without the need for opening the cell.

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Empowering the Future for En Route Charging Infrastructure

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1 Introduction

1.1 Policy Context

As Europe transitions to a more sustainable future, electric vehicles (EVs) will have an important role in reducing carbon emissions in the transportation sector. The EU has mandated that all vehicles sold in the EU must have zero carbon emissions by 2035 [1], which will greatly increase the EV fleet in member states. However, the widespread adoption of EVs requires a new approach to delivery of refuelling and recharging infrastructure across the EU.

To ensure consistent access to EV charging across the European Union and thus encourage drivers to switch, the EU has introduced the Alternative Fuels Infrastructure Regulation (AFIR) [2]. This specifies a minimum quantity of electric vehicle charging infrastructure along the TEN-T network throughout the EU. These requirements define:

- The distance between charge points along a route,
- The total charging pool at each location,
- A minimum number of charge points of a certain power rating.

The requirements vary whether the route forms part of the Core or Comprehensive TEN-T network and by vehicle type. The extent of charging infrastructure required by the regulation increases progressively in four stages from 2025 until 2035 with the two intermediate stages in 2027 and 2030. In addition to the requirements outlined above, AFIR requires the that the provision EV charging infrastructure will stay ahead of demand by mandating that the total publicly accessible EV charging capacity must increase proportionally with the number of EVs on the road through providing.

- 1.3 kW per Battery Electric Vehicle (BEV)
- 0.8 kW per Plug-in Hybrid Electric Vehicle (PHEV)

Ireland's Climate Action Plan 2023 outlines the pathway to cut transport emissions by 50% by 2030. The most significant mitigation action is the transition of 30% light duty vehicles to be fuelled by electricity by 2030. To enable this transition, the Department of Transport's Electric Vehicle Charging Infrastructure Strategy (EVCIS) 2022–2025 set

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out ambitious targets for the deployment of EV charging infrastructure across Ireland. These include a particular focus on the development of a comprehensive high-power charging network along our national roads. As part of the implementation of the EVCIS, the Draft National En-Route EV Charging Network Plan, informed by the Agent Based Model scenarios presented in this paper, provides a roadmap for the deployment of en-route charging infrastructure, working towards achieving both national and European ambitions for cleaner transportation.

1.2 Existing Infrastructure Provision in Ireland

As of 2023, the level of EV charging infrastructure along the TEN-T network in Ireland generally falls below the levels required by AFIR. The existing network of service areas does not cover the TEN-T network at the distance thresholds defined by AFIR, especially along the single carriageway portion of the network. Addressing these issues to ensure compliance with AFIR is a key priority for Transport Infrastructure Ireland (TII), the road authority, as well as supporting the government's ambition for a zero emission fleet, by implementing appropriate charging infrastructure.

The delivery of EV charging infrastructure, both along the TEN-T network and more broadly, is complex. It does not merely require the identification of sites and the extent of facilities required at each location but also requires coordination with the national electricity grid operator, ESB Networks, to ensure sufficient electricity supply for anticipated demand levels. Widespread EV uptake has the potential to greatly increase the demands on the electricity grid, and as such it is crucial for TII to understand both the magnitude of electricity demand resulting from EV charging, its geographical distribution, and its temporal profile across a day through modelling insights.

2 Agent Based Modelling

Agent Based Models (ABM) are an approach to modelling that simulate the travel decisions at the level of an individual. This differs from traditional strategic models which are based on aggregated travel patterns between zones. Detailed characteristics on demographics and activity plans can be assigned to each agent, which influence their travel choices as they interact with the transport network and each other.

This level of detail means that ABMs can provide insight into a wide range of questions that more aggregated transport models struggle to answer. An ABM outputs detailed information on the daily routes of all agents, and this information can thus be sliced and cross-compared in many ways. Some of these include the environmental and equity impacts of transport strategies, the potential for mode shift among different population groups, and multi-modal travel.

3 Modelling Electric Vehicles in an ABM

Given their granularity, ABMs can also be used to model the behaviour of electric vehicles. The outputs from a MATSim model include the mode that each agent used and their travelled route throughout the day, including speed information. Through applying battery capacities and rates of charging and consumption, it is possible to derive the charging profile of each electric vehicle, and through postprocessing understand their aggregate demand on transport and electricity grid infrastructure.

These principles are applied in BatSim, a tool developed by Arup that models EV battery consumption and charging demand by postprocessing the outputs ABM simulations. Within this tool, each agent's battery level is tracked as they drive and recharge. Agents aim to recharge in a way that minimises their cost in both time and money. Home charging (or depot charging for freight vehicles), where available, is thus the most attractive option as agents are generally based there overnight. Charges during activities are generally the next most popular, as they do not add a time penalty to agent's daily plan of activities.

If an agent is unable to charge sufficiently while at home or during other activities, the drop in their battery level will trigger a 'desire to charge' while driving. Agents will, however, try to avoid en route charging due to its significant time penalty compared to refuelling for petrol or diesel.

The principle of how choices in charging apply to different agents is illustrated in the diagram below. Alice charges only at home, despite also having access to charging at work or the supermarket, as home is her longest activity in the day. Bryan cannot charge at home, so instead chooses to charge at work where he has access to charging. Carl, meanwhile, cannot charge at home, work, or the supermarket, and thus has no alternative but charge en route both on the way to work and on the way home (Fig. 1).

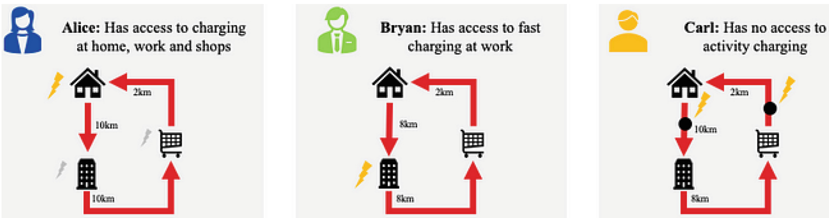

Fig. 1. How charging behaviour varies among agents with different access to EV charging during their activities.

Given the granularity of an agent-based model, the characteristics influencing a given agent's likelihood of owning an EV and their charging behaviour can be assigned based on their attributes. For instance, agents with different income groups or living in different house types or geographic areas may be more likely to own an EV, agents living in a detached house may be more likely to have access to home charging, and workplaces or supermarkets in suburban areas may be more likely to provide EV chargers than those in city centres.

The BatSim tool allows many scenarios concerning EV uptake and access to charging infrastructure to be tested rapidly, and thus allows the range of potential impacts to be understood.

4 Applying EV ABM Simulation in Ireland

4.1 Key Assumptions

In applying EV modelling through an ABM to Ireland, assumptions on the uptake of EVs and access to charging infrastructure were developed. These informed the scenarios that were passed to BatSim for analysis. In addition, synthetic populations for 2030 and 2035 were utilised, corresponding to target years referred to in the AFIR.

To develop scenarios for EV uptake, the total number of EVs in the national fleet was first determined, and then these were assigned to agents based on income category and their home location. Three main scenarios for a national fleet were utilised, based on the Irish Government's Climate Action Plan targets and potential scenarios for EV uptake developed by SIMI and Eirgrid. The total numbers for EV cars were:

- Low penetration – 210,000 in 2030, 540,000 in 2035
- Medium penetration – 560,000 in 2030, 980,000 in 2035
- High penetration – 870,000 in 2030, 1,450,000 in 2035

These were then probabilistically assigned to agents based on three categories of income and six categories of urban-rural home location. It was assumed that agents with higher incomes and living in urban locations were more likely to own an EV, with those of lower incomes and in rural locations less likely to do so. This was based on the relatively higher cost of purchasing an EV, and the perception of range anxiety for people who drive longer distances as is more common in rural areas of Ireland.

Some further details were applied to the modelling:

- A range of battery sizes from 30 kWh to 100 kWh were assumed, with higher income agents considered more likely to own a higher capacity battery.
- 30% of EVs were assumed to be PHEVs, based on research by the MaREI Institute [3], which were assumed to not charge en route as they would likely fill up with petrol or diesel instead if required.
- EV uptake among light goods vehicles (LGVs) and heavy goods vehicles (HGVs) was also assumed based on the Climate Action Plan, with lower rates than for cars.

Also, five scenarios for EV destination charging were developed. For each scenario, the likelihood – from very low to very high – of accessing either slow (7 kW), medium (11 kW), or high (22 kW) speed chargers was assigned for each of three location types – on-street in urban areas, on-street in rural areas, and destinations.

4.2 BatSim Outputs

BatSim generates a dataset which records 'desire to charge' events among agents with an EV. Each of these events has several attributes, including: a timestamp, a geographic coordinate, a duration, a quantity of charge, a type of charging event, such as home, destination, or en route. These can be associated with geographic locations and/or agent attributes to enable aggregation and further post-processing analysis (Fig. 2).

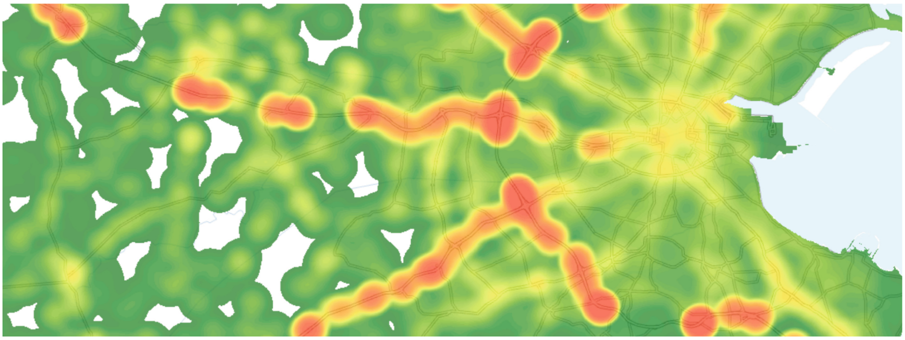

Fig. 2. ABM output depicting geographic distribution of 'desire to charge' events. Image produced using ArcGIS Pro.

4.3 National and Regional Level Outputs

One postprocessing step for BatSim outputs is to analyse the scale of EV charging demand across a network. This allows comparison of total energy demand across a range of scenarios, giving an indication of the extend of energy demand from EVs relative to other sectors of the economy. Demand can be segmented in a number of ways, such as geographically by local authority or energy grid region, or through charging event types. An example of this approach is presented in the image below, which shows national EV demand for a range of different EV uptake and access to infrastructure scenarios as discussed in Sect. 3. This analysis shows how overall EV energy demand increases as EV uptake increases, while lower levels of access to on street and destination charging result in an increase in the proportion of charging demand that occurs en route from a minimum of 5% to a maximum of 14% (Fig. 3).

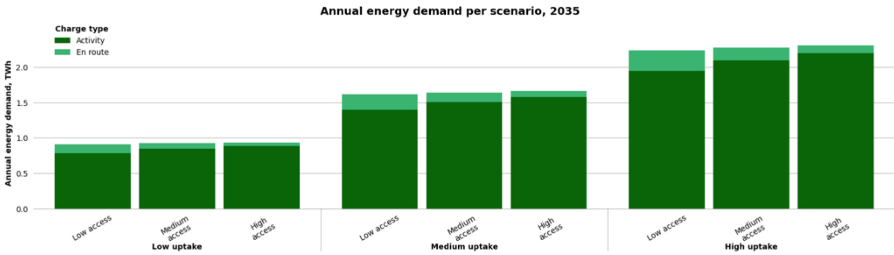

Fig. 3. Annual energy demand from EVs based on EV uptake and destination/on-street charging access scenarios.

The temporal profile of different types of EV charging demand can also be analysed from BatSim outputs. The figure below shows the profile for an urban area which has lower access to home charging (as a higher proportion of residents live in apartments or terraces). It is notable that en route charging tends to peak in the same morning and evening peaks as general traffic, destination charging peaks in the morning as many agents arrive at work, and on street and home charging peak in the early evening as agents return home (Fig. 4).

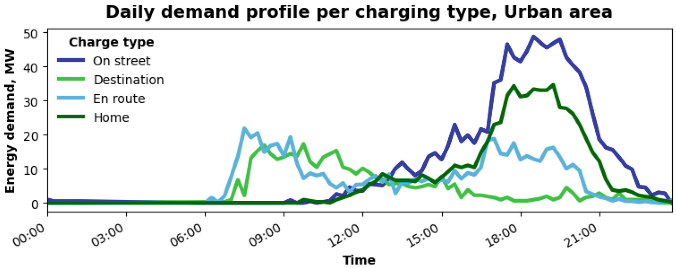

Fig. 4. Temporal profile of different types of EV charging demand

This information is useful on a system level for understanding the impact of EV charging on the energy grid and what potential there is to mitigate it. For instance, it may be possible to smooth the peaks in demand from home charging through smart chargers or pricing strategies, whereas en route charging peaks may be more challenging to reduce. Insights can also be drawn in relation to wait times at potential charging pools.

Scenario testing can also inform decisions in relation to government supports or interventions may be required due to market failure in areas of low demand.

4.4 En Route Charging Infrastructure

Using similar logic to that described in the previous section, it is possible to determine the scale and temporal profile of EV charging demand at particular en route charging locations. This analysis has been used by TII & Zero Emission Vehicles Ireland (ZEVI) to understand the location and scale of demand for en route EV charging along the National Road Network, helping to determine if the requirements of AFIR are sufficient to meet potential future demand in particular locations (Fig. 5).

This approach requires en route 'desire to charge' events to be assigned to particular locations, as for en route charging events the geographic location output from BatSim notes the location where the agent's battery fell below the level at which they seek to charge. These charge events are assigned to the nearest potential charging location. The locations have been initially estimated utilising a mix of existing service areas and potential locations on the unserved parts of the TEN-T network that satisfy the minimum distance spacing thresholds defined by AFIR.

The analysis allows the variation in demand, geographically and temporally, across the network to be seen. This helps inform the scale and locations of infrastructure that will help Ireland in its transition to EVs over the coming years.

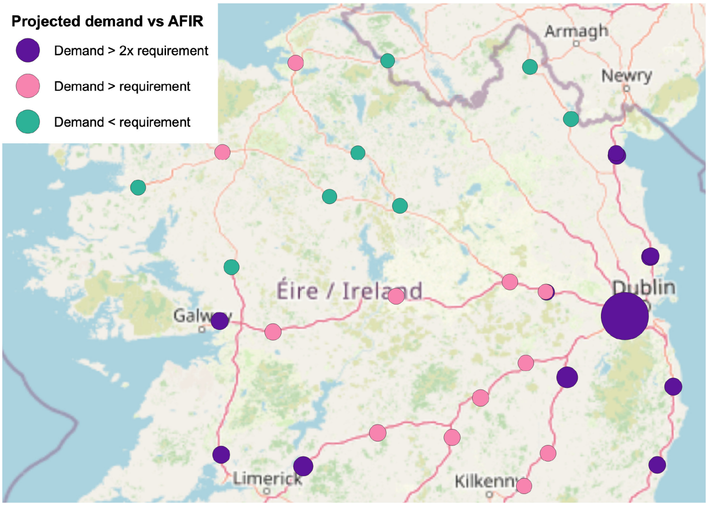

Fig. 5. Comparison of potential charge pool locations on Ten-T with AFIR minimum pool sizes. Image produced using ArcGIS Pro.

5 Conclusion

ABMs are an increasingly important part of the transport modelling landscape, with their granularity and ability to give insight into questions that more aggregated models are less well suited to. The applications of the EV modelling tool BatSim are an important addition to the capabilities of ABMs, helping to analyse complex real-world questions through scenario driven approaches. The work undertaken is contributing to ZEVI's development of Ireland's National En Route EV Charging Network Plan, and its capabilities have future application in analysis of the interactions between the transport and energy systems to secure delivery of Infrastructure.

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Ecosystem Analysis of the Battery Train, Today and in the Future

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Abstract. Rail is mainly a decarbonized mean of transport, but a portion of the railway network remain unelectrified and currently operated with diesel train. Trains with onboard batteries are a solution to maintain the same operation on these sections while avoiding GHG emissions but are complex systems that raises several questions regarding operation & infrastructure. While a separated solution could be investigated by each actor (operator, infrastructure manager), the goal is to minimize the life cycle cost of a railway system. In this article the French existing regional trains rolling stock fleet, the existing infrastructure or the new partial electrification evolution, and the operation modes are considered to evaluate the issues and opportunities brought by battery trains.

Keywords: Long range battery train · future asset management · smart charging strategies · operation robustness · battery lifetime management · rail system design

1 Introduction

The railway network has a length close to 230 000 km of lines for the EU 27 and the United Kingdom. Although an average of 60% is electrified today in Europe [1], the electrification and length of the railway network is very different between each country such as in the United Kingdom (33% of electrification), Romania (37%) or Czech Republic (34%). This situation of low electrification rate can be explained by many reasons, like expensive costs to electrify the railway lines, especially with bridges and tunnels. The costs of electrification can be not suitable economically if the railway traffic is too low. Consequently, it is important to consider "alternative drive trains" which run with energy sources other than diesel fuel, to maintain the traffic while minimizing costs at railway system level, energy consumption and CO_2 emissions.

In this paper, we will focus only on one of these technologies, the battery train, commonly called Battery Electrical Multiple Units (BEMU). An analysis of the future fleet of the battery trains in France will be presented in this paper, considering the evolution of the infrastructure, operation, and onboard lithium batteries capacity.

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2 BEMU State of the Art and Ecosystem

Nowadays, in Europe, there are around 600 battery trains ordered. The autonomy of this first generation of battery trains is about 80 to 100 km on non-electrified lines, as can be seen on Table 1, driven by the German market demand [2].

Table 1. BEMU trains ordered, sorted by expected range.

Country	Manufacturer	Order	Expected range
Austria, Denmark, France, Germany, Ireland	SIEMENS, BOMBARDIER, ALSTOM	90	40–80
Germany	ALSTOM	66	120–130
Germany	STADLER	113	150
France, Germany	ALSTOM, CAF	60+	200
Wales	STADLER	36	unknown

Around 50% of the French regional fleet, some 1,200 dual mode or diesel-powered trains, is responsible for 55% of the SNCF group's GHG emissions. That's why it has been decided to first focus on decarbonizing this fleet.

Considering an existing regional train with 3 to 6 cars in France, it was estimated that with an 80 km autonomy, 55% of the daily journeys could be done [3]. With an onboard 200km autonomy, the battery train would be able to do 88% of the daily journeys at iso operation (turnaround time, schedule and stop time in stations) and infrastructure. For the remaining 12%, solutions can be found on rolling stock level (more onboard energy, usage of hybrid diesel or hydrogen trains), on operation side (more trainsets, schedule modification) or infrastructure side by partial new electrifications.

All these solutions can be suitable, nevertheless, the goal is to minimize the life cycle cost of a railway system.

The operation side lever goes against the current trend in France to increase the frequencies of the trains, at iso-fleet to minimise the cost. So, it is not used in France.

Buying new trains, with more energy onboard, like those proposed by CAF or Alstom [4], is a solution, but in France the regional fleet is rather new and retrofit of diesel multiple units or dual mode trains is necessary. Indeed, the first hybrid, battery and hydrogen trains are retrofitted from Regiolis (400 trains, 15 years old) and AGC (700 trains, 20 years old) series [4, 5]. The advantage of the retrofit is the low investment cost of the rolling stock, the drawback is the constrained energy that can be stored onboard – for the given nowadays chemistries LTO or NMC.

Finally, only one lever can be used today in France to achieve 100% of the traffic decarbonization: to build new partial electrification for the retrofitted battery trains.

As the infrastructure could be expensive and the necessary time to build it could also be long, it is preferable to optimize the usage of the battery trains (to recover the braking energy, to reduce the auxiliaries' consumptions, to charge fast under each existing meter of catenary, …) and to minimize the investment in infrastructure. Two factors are very influent in infrastructure design (and cost): the operation mode (express – omnibus, all-out or schedule operation) and the degraded modes.

In a previous study [6] it was highlighted the differences between an all-out and the schedule operation. Statistical measurements shows that a realistic operation (which consider some departure delays) is a mix between all-out and the schedule operation on different interstation and this mix led to less energy needs (−11% in our study compared to all-out operation) and less infrastructures costs (−13%).

The battery-powered train introduces a new concept of "finite energy". Until now, whether in electric-catenary or diesel mode, energy could be considered unlimited (infinite in electric mode and around 1000 km in diesel mode for our regional trains) and degraded modes mainly involved the power limitations without the risks of running out of energy.

Today, this is no longer the case with battery-powered trains. This forces us to think beyond the rolling stock, with a system vision (train - infrastructure - operation) that is essential and leads us to identify new scenarios to address to obtain a high-performance, robust, and economically optimized result. This step of degraded modes analysis is crucial and need a huge work (gathering a large amount of data, involve a wide range of contributors) to address properly the battery train topic.

Once the initial rolling stock and infrastructure design assumptions have been set for a given line, rolling stock and operation, performances can be analyzed for different degraded modes:

– degraded train modes: Reliability objectives at train level are defined at the beginning of the project and are classified by impact on operations. To meet these goals, many levers are available during the design phase, such as system redundancy, predictive maintenance, functional fallback, or choice of robust components.
– degraded infrastructure modes: The power supply is a key element to ensure a robustness operation. That's why specific calculations are needed concerning unavailable infrastructure scenarios (substation out of order, forgotten pantograph lift, etc.) to characterise the battery train's ability to complete its mission, or even to continue the journey without request for assistance.
– degraded operating modes: To evaluate the resilience of our design solution (rolling stock + infrastructure), it is necessary to study the main degraded operating cases (impact of delay of other trains, fatalities, …). This could also lead to establish new operating procedures to be put in place during these disrupted situations.

3 Influence of New Charging Infrastructure for Battery Trains

Building new partial electrification for the retrofitted battery trains remains a challenge. Due to high costs, electrification should be anticipated for years and carefully planned. The example below illustrates various possibility on a French railway line. It is 36 km long with a short 2.5 km long electrified section at the beginning and reduced turnaround times.

Without infrastructures, a roundtrip (gray line on Fig. 1) is neither sustainable (lowest SoC 25%) nor robust to exploitation hazards. Moreover, it heavily strains the battery, decreasing its lifetime.

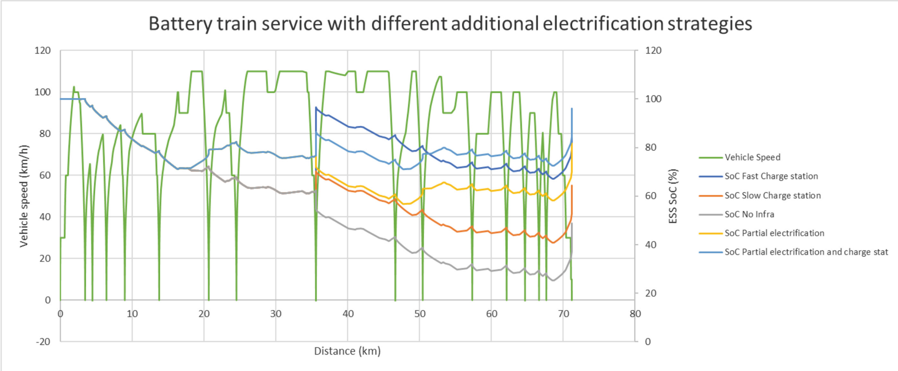

Fig. 1. Speed of a train (green) and SoC on a roundtrip for various electrification options

Several solutions were studied to tackle those issues. The first one is the electrified section. To minimize the cost of electrification, an analysis of the environment of the line was made to find the simplest area to electrify. A partial electrification of 5 km in the middle of the line, between kilometer 18 and 23 (uphill) or 48 and 53 (downhill), was found as optimal (yellow line on Fig. 1).

The second one is an additional charging station. On the railway line selected for our study, we took the assumption to create a single charging station at the end station of the uphill way (station I). Thanks to this additional infrastructure, the lowest SoC is improved (40%, see orange line on Fig. 1). Moreover, it is interesting to keep active the auxiliary loads on board during turnaround time at the end station, especially the ones for passenger's comfort.

By combining partial electrification and charging station, the lowest SoC value is around 73% (see light blue line on Fig. 1). It is almost 3 times better than the current situation without additional infrastructure. This will improve the limitation effect on SoC and so favorize the lifetime. With this solution, the exploitation is robust: If the partial electrification or if the charging station is not available, the operation can continue.

4 Impact of Regulation and Standards

For DC voltage, current limitation at standstill is considerably reducing the charging power level. In 1.5 kV DC, used in France, the current limitation value is 300 A, so it means 450 kW to be dispatched between train loads, losses of energy conversion and finally, charging for the traction batteries. Having a limited charging power can extend the time needed to obtain full or enough energy capacity in the traction batteries for the next operation. For the 25 kV 50 Hz AC voltage used in France, the current limitation value is 80 A, which gives 2000 kW, more than 4 time the power level allowed for DC voltage supply. While the orange line on Fig. 1 represent a DC charging station, the dark blue line on Fig. 1 represents an AC charging station.

This option is very interesting because during the turnaround time in the station I, we can recharge almost fully the batteries with the fast charging (95%) before going back to the return trip. The lowest SoC here is 67%.

5 Potential Issues and Opportunities of BEMU Trains

Many countries around the world are facing the challenge of energy crisis. Especially in Europe since more than 1 year now, energy costs have increased significantly and so, affected the economy. BEMU trains are also impacted by these topics.

The first issue regarding battery trains fleet is the charging power. Charging may occur during running or during parking. Especially for parking, the charging power increase the current level compared to conventional electric train. This is impacting the infrastructure and the power supply that must deliver the high power requested by battery trains charging. For several BEMU charging simultaneously, the power repartition should also be monitored and controlled, which may not be the case for the 1st generation of BEMU. This is a new problem to solve for railway sector. Data exchange should be necessary between trains and infrastructure to create this efficient management of energy. Operation data could be integrated as well in the exchange process to avoid negative impacts on service.

The second issue is on the preservation of battery lifetime. With degradation from the battery comes capacity reduction, up to −20% at the end of life. This reduces the range in catenary free operation. To minimize traction batteries ageing, charging strategies are important. For example, fast charge should be used only when necessary. Equally, a good accuracy of estimated consumption during operation is key to avoid any "low battery" and the consequences regarding operation traffic or comfort. If a partial new electrification is built today for a robust operation of an 80km BEMU, it can be imagined that in 10 or 30 years it will be used differently when the energy stored onboard will significantly increase (from 30 to 150% as showed in different roadmaps [7]), allowing for more flexibility in the usage of degraded batteries in the future. Future research will investigate this opportunity to quantify its benefit.

Another way to conserve battery lifetime is to change the operational lines of the battery train with one that puts less strain on the battery usage. Thus, a degraded battery could still be used until its initial lifespan is reached to maintain the operation. Future research will address this to get insights on operation options & impacts on battery life.

Finally, battery trains may be also used for supporting energy grid by providing, absorbing, or being disconnected from the grid (load shedding) [8] or to support renewables [9]. The charging or discharging strategies must be defined in a collaborative approach to ensure battery lifetime preservation, while giving flexibility for energy stabilization of the grid.

6 Conclusion

This paper described a manner of thinking the battery trains deployment in France, considering the existing regional trains rolling stock fleet, the existing infrastructure or the new partial electrification evolution, and the operation modes.

It is showed that battery trains, with limited energy onboard, are complex systems. Evolution of the lithium batteries technology and the deployment of few new partial electrification today are complementary and is not incompatible in time.

Many variables, like battery technology, operation and infrastructure contribute to a minimal life cycle cost of the battery train concept in France. Nevertheless, studies are necessary each time it is necessary to decarbonize a territory.

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E-VOLVE Cluster: Increasing Innovation Efficiency to Support the Transition Toward Sustainable e-mobility

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Abstract. The transition to e-mobility is disrupting the automotive market. To facilitate this transition, the European Commission with the support of the 2ZERO partnership is calling for experts to engage in collaborative R&D programs, and develop pre-competitive solutions and methodologies supporting the uptake of e-mobility. The target of this paper is to provide an overview of the granted European projects running under the umbrella of the E-VOLVE cluster, illustrating the complementarity of the different initiatives as well as their coverage of the main priorities as defined by ERTRAC. The focus is set on the targets and outcomes of the projects HiPE, HighScape, RHODaS, SCAPE, EM-TECH and Multi-Moby, addressing innovative components (power electronics, e-motors), advanced control strategies, and circularity for safe, efficient, affordable and sustainable e-mobility.

Keywords: e-mobility · power electronics · e-machine · sustainability

1 Introduction

Undoubtedly, the transition to e-mobility is one of the most important trends in the automotive domain to address the societal challenge to drastically reduce emissions (Paris Agreement [1], European Green Deal [2]). All European carmakers are strongly committed to the uptake of e-mobility – the number of electric vehicle models launched

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and planned is rising from 50 models in 2018 to >250 in 2025 [3]. This trend is further confirmed by the market share of battery electric cars that almost doubled to ~10% in 2021 [4]. The automotive sector is looking for: (a) technology solutions able to address the changing users and market needs; (b) increased user acceptance for e-mobility through affordable, energy efficient systems implementing innovative and holistic user-centric solutions providing high comfort and safety; (c) agility and first mover advantage through accelerated design and testing methodologies; and (d) sustainable technologies to minimize the environmental footprint throughout the entire lifecycle of the vehicle (production, operation including charging, end-of-life). In this context, the E-VOLVE (Electric Vehicle Optimized for Life, Value and Efficiency) cluster [5] explores and exploits synergies between European projects launched within the 2ZERO program. This paper presents the ongoing projects and discusses the complementarity of these approaches to support the uptake of affordable, sustainable and user-centric e-mobility, while strengthening European competitiveness.

2 The Collaborative Projects

2.1 HiPE

The HiPE project aims to develop a new family of highly energy efficient, cost-effective, modular, compact and integrated wide bandgap (WBG) power electronics solutions for the next generation of battery electric vehicles (BEVs). The projects outputs will include (a) a scalable and modular family of WBG-based traction inverters with significantly improved specific cooling performance, suitable for 400 V, 800 V and 1200 V applications, with power ratings from 50 to 250 kW, integrated into electric drives including the high-to-low voltage (HV/LV) DC/DC converters, thus enabling drastic size and weight reductions; (b) a family of integrated WBG-based bidirectional on-board chargers (OBCs) and HV/LV DC/DC converters, with optimized innovative topologies, including use of Gallium Nitride (GaN); and (c) integrated, fault-tolerant and cost-effective GaN-based power electronics for high-voltage ancillaries and chassis actuators. The HiPE smart power electronics solutions will include intelligent and predictive controllers to optimize performance, innovative and computationally efficient data-driven approaches to monitor the state-of-health of the relevant hardware, as well as novel self-adaptive digital-twin-based methodologies to tailor the component- and vehicle-level algorithms to the specific condition of the hardware installed on each individual BEV, and actively improve reliability and availability of the electronic parts during field use. For this, four experimental Use Cases (UCs) were developed covering the HiPE outputs: UC1: Integrated WBG-based traction inverters, HV/LV DC/DC converters and electric motors for high volume passenger vehicle up to 150 kW; UC2: Integrated WBG-based traction inverters, HV/LV DC/DC converters and electric motors for light commercial vehicles; UC3: Integrated WBG-based on-board chargers and HV/LV DC/DC converters; UC4: Integrated and fault-tolerant power electronics for ancillaries and chassis components.

2.2 HighScape

HighScape envisions a series of research and innovation activities to develop, test, and validate innovative solutions for next-generation BEVs that can only be achieved through the latest wide bandgap (WBG) technologies. HighScape will focus on BEV architectures with distributed multiple wheel drives and, in particular, in-wheel direct drive powertrains, and will explore the feasibility of a family of highly efficient, integrated, compact, low-cost, scalable, and modular power electronics components and systems, including integrated traction inverters, on-board chargers, DC/DC converters, and electric drives for auxiliaries and actuators. The proposed solutions will achieve automotive quality levels with robust and reliable functionalities that will be evaluated and validated on test benches and on two differently sized BEV prototypes. The project will lead to the following results: (a) component integration at a level not achieved before, e.g., with the installation of the WBG traction inverters in the in-wheel machines; the functional integration of the traction inverter with the on-board charger, and the integration of the latter and the DC/DC converters in the battery system; and the implementation of multi-motor and fault-tolerant inverter solutions for the auxiliaries and chassis actuators; (b) implementation of reconfigurable winding traction drive topologies, and integrated and predictive thermal management at the vehicle level using phase changing materials in the power electronics components; (c) achievement and demonstration of significantly higher power densities, specific powers, and energy efficiency for the resulting power electronics systems and associated drives; (d) significant cost reductions over the current state of the art due to dual use of parts, modularity of subsystems, and model-based design to avoid over-engineering; and (e) increased reliability of power electronics systems, enabled by design and intelligent algorithms for predictive condition monitoring.

2.3 RHODaS

The objective of the RHODaS project is to develop disruptive high-power modular power inverter topologies for e-axle Integrated Motor Drive (eIMD) to be used in all-electric heavy-duty long-haul vehicles over 12 tonnes. RHODaS uses new WBG semiconductor materials as well as cutting-edge digital technologies to improve architectural efficiency, power density, reliability, cost, and sustainability, to develop a high power SiC – GaN hybrid power inverter up to 250 kW/1000 V. RHODaS's main contributions are: (a) development of hybrid high-power T-Type multilevel inverter topologies, up to 150 kW/250 kW rated/peak power. The volumetric and gravimetric densities of the power converter are expected to be 100 kW/l and 50 kW/kg respectively; (b) study of components and advanced thermal management strategies. The advanced thermal management system can extend working temperature ranges up to 150 ºC using combined air-liquid solutions; (c) assembly of the converter coupled to the motor casing. This assembly will increase the power density of the traction drive up to 33 kW/L; (d) ensure the sustainability of the designed converter and its components throughout its life cycle; (e) integration of analogue and digital drivers with the high voltage WBG materials, including protections and fault detection circuits; (f) development of new control and modulation techniques to reduce switching losses and total EMIs, while improving reliability and control; (g) integration of new sensor networks at the material, component and system level to provide real-time data for remaining useful life (RUL) prediction's accuracy of 75%; and (h) development of integrated and modular IMD designs to be applied in "multi-axle traction" concepts for heavy-duty long-haul trucks.

2.4 SCAPE

The SCAPE project proposes a standardisable, modular, and scalable approach for the design of the BEV power conversion system, based on multilevel neutral-point-clamped power converters. This approach has a great potential to reduce the cost of BEV power electronics thanks to scale economies, suitable for a wide range of BEV applications (from two-wheelers to heavy-duty vehicles), to allow to take full advantage of chip-embedding (CE) board integration technology, and to enable advanced functionalities such as online diagnosis, digital twin, and predictive maintenance. The SCAPE expected outcomes are: (a) EV power electronics cost decrease by 30–40%, achieved through the combination of economies of scale, CE, reduced weight, less design expenses, and better reliability of the system; (b) powertrain losses reduction by at least a 35%, and specific-power figures beyond 30 kW/kg and power-density beyond 100 kW/litre, thanks to the higher efficiency of the multilevel converter topology, the higher performance and compactness offered by CE technology, the reduced need of heat dissipation, higher switching frequency (reduced size of passive power filters), and the advanced control strategies; (c) advanced converter designs featuring an integration of the traction inverter and the on-board charger, allowing to further reduce the power electronics volume and cost; (d) modular and flexible design provided by the use of interconnected building blocks, and CE technology that can be adapted to any available space and shape within batteries, or coupled to electric motors yielding a highly compact system; and (e) monitoring system integrated within the building block, which provides information to an advanced control system linked to a digital twin to enable optimal operation with increased lifetime and early detection of failures. In addition, the SCAPE powertrain inverter topology is inherently fault-tolerant and can remain in operation after the failure of one or more building blocks. The SCAPE outcomes will be validated with a prototype of the integrated inverter/OBC and the auxiliary DC/DC converter in a relevant environment. The prototype is based on the use case of a medium-size battery electric car, with 100 kW of power and 800 V traction battery.

2.5 EM-TECH

EM-TECH brings together 10 participants from industry and academia to develop novel solutions that push the boundaries of electric machine technology for automotive propulsion through: (a) innovative direct and active cooling concepts; (b) virtual sensing for the high-fidelity real-time estimation of the machine's operating conditions; (c) improved machine control that brings the design and operating cost savings enabled by (b); (d) electric gearing to improve operational flexibility and energy efficiency; (e) digital twin-based optimization that incorporates the systematic consideration of life cycle analysis and life cycle cost aspects from the early design stages; and (f) use of recycled permanent magnets and circularity solutions. The proposed innovations will be implemented in a new series of radial flux direct drive in-wheel motors, featuring unprecedented torque density and specific power (>150 Nm/litre, >50 Nm/kg), as well as in ironless axial flux machines with one stator and two rotors, offering power density and specific power above 30 kW/litre and 10 kW/kg. The solutions will be suitable for both car and van applications (continuous powers of 50 kW–120 kW), will offer competitive costs (<6 Euros/kW for a production of 100000 units/year), and will lead to a significant reduction of the energy losses of the motor during real vehicle operation (>25%), as well as to >60% reduction of rare earths, including magnet recycling solutions. EM-TECH will also support the development of European leadership in key digital technologies and the development of the corresponding value chains.

2.6 Multi-Moby

Multi-Moby is an elaborate project, using recent developments and results from a series of ongoing and past EU Horizon projects, to generate new technologies for safe, efficient and affordable urban BEVs. The Multi-Moby BEVs consist of vans, pick-ups, and passenger vehicles, which share the same Super High Strength Steel body frame, manufactured in a microfactory based on low-investment and lean processes. Despite their low cost, the Multi-Moby BEVs have excellent passive safety characteristics, verified with crash test experiments. The vehicles are further enhanced with vehicle-to-everything (V2X) based active safety controllers, e.g., pre-emptive braking, pre-emptive traction control, and pre-emptive antilock braking system (ABS) functionalities. In addition, Multi-Moby has assessed newly developed gimbal-based camera systems for environmental detection, as a low-cost alternative to lidars and radars for automated driving solutions. The Multi-Moby BEVs are 4-wheel-drive, consisting of two on-board centralised powertrains with 100 V and 48 V powertrain options (with corresponding battery pack voltages). This includes newly developed 15 kW (per axle) 100 V permanent magnet assisted synchronous reluctance motors (PMaSRM), or 9.5 kW (per axle) 48 V powertrains with belt transmissions. Besides the 100 V and 48 V battery pack options, a novel 48 V hybrid supercapacitor-battery pack with cylindrical cells has been developed. The hybrid supercapacitor-battery cells combine the high-power density of supercapacitors with the high energy density of batteries. Fast charging is provided by a novel 7 kW DC wall box charger, based on the latest generation of SiC-based MOSFETs which can reduce charging losses.

3 Addressing the ERTRAC Research Needs

Figure 1 provides a mapping between the "research needs for powertrain" according to the European Road Transport Research Advisory Council (ERTRAC) [6] and the initiatives introduced in this paper. Clearly, all projects address "modelling and simulation" as well as "advanced components, materials and processes" – which are the core of the calls addressed by the projects in the E-VOLVE cluster. Furthermore, environmental sustainability is a key research topic for most of the projects. Still, each project has its own specificity by addressing different BEV systems and different application domains. Summarizing, the projects represented in the E-VOLVE cluster are highly complementary to cover the European vision toward zero emission road transport.

	Research Need for Powertrains	HiPE	HighScape	RHODaS	SCAPE	EM-TECH	Multi-Moby
Method.	Modelling and simulation	X	X	X	X	X	X
	Connectivity and data management						X
	Recycling, Materials for New Powertrains			X		X	
	Availability / Sustainability of resources	x	x	x	X	X	
BEV	Advanced Components, Materials and Processes	X	X	X	X	X	X
	Connected and AI-based systems		X			X	X
	System approach, vehicle integration	X	X				X
	Safety test procedures and technologies						X
	Charging technologies (bidirectional, comfort-charging, robotic)		X				X
	Battery Swapping technologies						
	Data acquisition and AI supported development						
	Implementation of eco-design principles			X	X	X	
Appl. domain	Light electric vehicle				x		X
	Passenger cars	X	X		X	X	X
	Light commercial vehicles				x	x	X
	Heavy-duty			X	x		

Fig. 1. E-VOLVE projects coverage regarding the ERTRAC roadmap [6] - Image courtesy of E-VOLVE cluster, reproduced with permission.

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Energy and Fuel Transition

Physical Modelling of Container Ship Propulsion and Comparison with Operational Data

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Abstract. International Maritime Organization (IMO) has adopted a strategy to reduce at least 50% of GHG emissions from the global shipping sector by 2050, compared to 2008. Preparing for these requirements, a 4-year R&D project, TNTM (Digital Transformation of Maritime Transport) was initiated. As part of this project, the current work presents the physical models that compares their outputs with actual on-board measurements on a LNG powered containership. The main propulsive systems were modelled using SEECAT (Ship Energy Efficiency Calculation and Analysis Tool), an in-house tool developed by Bureau Veritas Marine & Offshore. A custom hull performance model was developed assuming the vessel's static equilibrium under the different forces and moments. The later have been estimated through CFD and includes calm water resistance depending on drift & rudder angles as well as added resistance by wave and wind. A simulation has been performed for a complete rotation, which lasts about 3 months between Asia and Europe. The comparison of the numerical results and the data recorded at sea were carried out. A good agreement has been obtained, the root-mean-square error during the steady state of the engine power and the fuel consumption is 7.6% and 9.1% respectively.

Keywords: Maritime transport · emission reduction · ship modelling · environmental impact · energy consumption · on-board measurements

1 Introduction

For years, low oil price and regulatory constraints have not generated sufficient drive to reduce the energy consumption and emissions. However, in the current context of increasing energy price and global climate change, awareness has raised worldwide, and incentive are now stronger. Along with the policy initiatives envisaged by IMO, it becomes mandatory to optimize both the energy efficiency and the management of the operations as well as to introduce new fuels. Ship performance modelling is one of the key aspects as it will later enable to benchmark design or operational strategies in controlled and representative environmental conditions, whereas assessments through

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sea trials display inherent variability in the encountered environmental conditions which makes reliable analysis difficult. Considering that objective, ship performance models need, as a prerequisite, to reproduce accurately the performance on a route already performed by an existing vessel.

A simple model which uses a power vs speed curve, and a constant correction coefficient to account for the average sea state (Marty, 2014) may be used to predict the integrated fuel consumption of the whole voyage. However, this type of model is not precise enough for the instantaneous prediction since the weather condition can impact greatly on ship's performance. Several CFD approaches have been performed to evaluate the actual performance of a vessel for each element factor: wave resistance (Orych, Östberg, Kjellberg, Werner, & Larsson, 2023), roughness (Song, et al., 2020), wind (Janssen, Blocken, & Wijhe, 2017). These models are usually costly which does not allow a simulation during long period. (You, Kim, & Seo, 2018) modelled a complete propulsion system and compared with the measurement over a period of 14 days.

In this paper, a new method is presented which is hybrid between the CFD and the quasi-static model using SEECAT. This gives the advantage to increase the precision and to keep the model simple enough for a long run simulation. A simulation has been performed for a complete rotation (from point A and return to point A) of a LNG powered containership. The voyage lasts about 3 months between Asia and Europe. The comparison of the numerical results and the data recorded at sea was carried out.

2 Numerical Model

2.1 CFD Model

CFD model is composed of three different sub-models:

1. Calm water model
   Calm water resistance is evaluated through RANSE computations for two drafts, three speeds, three rudder angles and three drift angles. Values are interpolated in SEECAT to obtain the actual condition needed in the quasi-static model. 54 computations were performed.
2. Aerodynamic model
   Aerodynamic efforts are calculated through RANSE computations for one speed and one draft only, and for seven wind headings. Efforts are then transformed into coefficients that do not depend on wind speed, nor draft. 7 computations were performed.
3. In-wave model
   Efforts in waves are calculated with a cost-effective hybrid method. They are firstly evaluated for one speed, one draft and all wave headings through potential solvers. These potential efforts are then calibrated thanks to three RANSE computations in head waves only.

2.2 Quasi-Static Ship Performance Model

Figure 1 represents the propulsion system in the SEECAT model. This model does not use any tunning parameters, the equations are only based on the CFD calculations and the balance of forces and moment.

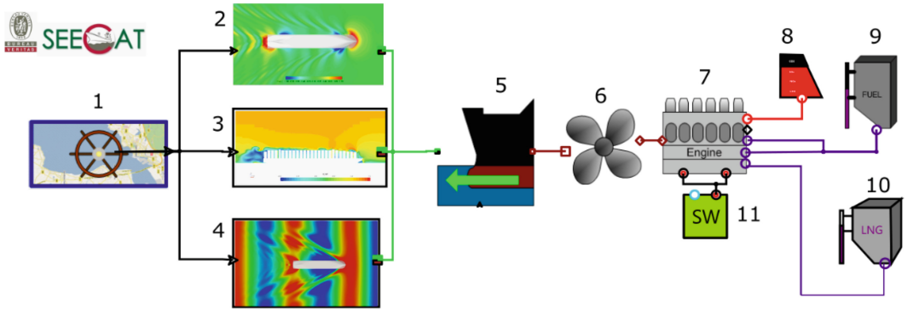

Fig. 1. Global model of propulsion system. Source: Authors

It includes:

1	Operation conditions: ship's speed, heading, wind & wave conditions
2–4	Calm water, wind and wave model to calculate the forces when wind and wave are not involved, aerodynamic forces and forces due to wave respectively. These models use the CFD pre-calculation results as inputs
5	Forces and moment balances where static equilibrium is applied. This model allows 3 degrees of freedom: force in x, y and moment in z: $(1-t)T_{propeller} + Fx_{calm} + Fx_{wind} + Fx_{wave} = 0$ $Fy_{calm} + Fy_{wind} + Fy_{wave} = 0$ $Mz_{calm} + Mz_{wind} + Mz_{wave} = 0$ These three equations allow to determine the ship's equilibrium among rudder angle, drift angle and thrust to achieve the commanded speed. t is the thrust deduction factor
6	Propeller model using open water curves
7	Dual fuel engine model, the fuel consummation is obtained through the specific fuel oil consumption curves given by the engine maker
8	Funnel where the amount of CO_2, SO_x, NO_x, CH_4 emitted during the voyage are estimated
9–10	Fuel and LNG tank
11	Sea water for engine cooling

2.3 Simulation Conditions

The simulation was performed for a rotation complete (from one port and returning to the same port) which corresponds to 95 travel-days between Europe and Asia. The simulation time is about 15 min on a standard laptop. For confidentiality reasons, all the variables will be shown in a dimensionless form which is defined as the ratio between the studied value and its maximal value: $X^* = X \big/ X_{max}$

Figure 2 shows the speed through water measured during the voyage. Ship is at port and sea-going when the non-dimensional speed equals 0 and around 1 respectively.

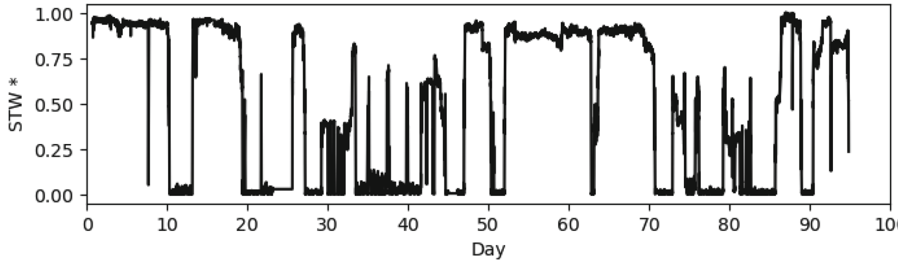

Fig. 2. Measured speed through water profile.

Figure 3 shows the wave and wind conditions. These values were obtained along the GPS position of the ship over time using Copernicus database. The red curve represents the apparent speed/significant height value of wind/wave. The black arrow indicates the incident angle relative to the ship. Ship is oriented horizontally heading to the right.

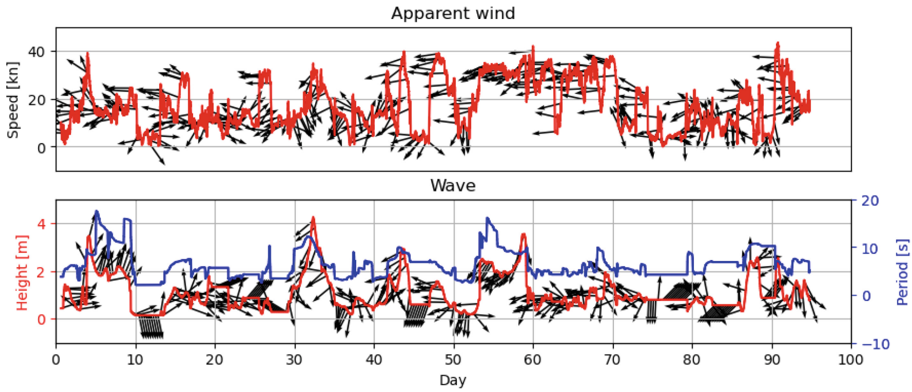

Fig. 3. Wave and wind conditions along the measured GPS location of the ship

3 Results and Discussion

In this part, the measured values are compared with the results of the numerical simulation. The engine power and the fuel consumption were chosen for the analyzes. Error is defined for a value X as: $error = \frac{X_{model} - X_{measure}}{X_{measure}}$

With the aim to quantify the error in one single number, root-mean-square error is also calculated: $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} error_i^2}$

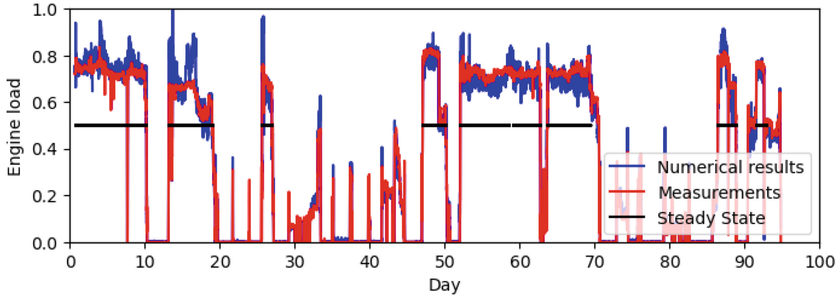

Fig. 4. Measured and calculated engine's load over time

Figure 4 shows the measurements (red line) and the numerical results (blue line) of the engine's load. Black lines indicate time periods which can be considered as steady state. In general, the predictions follow a similar tendency than the measured values.

Locally, the model sometimes over or under-estimate the results especially from day 13 to day 16. It can be partly explained by the fact that the model doesn't consider the dynamic behavior. A sudden change in the environmental conditions leads to the immediate change in the engine's power, which is not the case in the reality. For the same reason, only steady state is considered for the error calculation.

Figure 5 shows the frequency distribution of the steady-state error on the engine load.

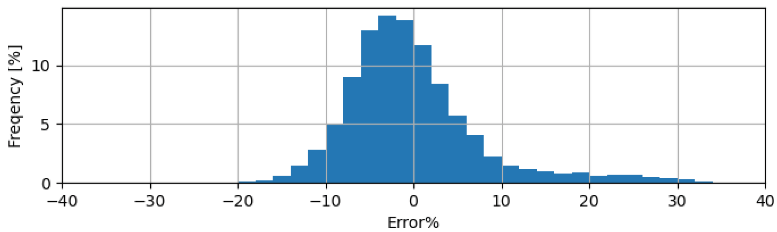

Fig. 5. Frequency of the engine power's error

The distribution is almost centered with a slight tendency to underprediction. Most of the errors are in the range between −10% and 10%. The steady-state RMSE of the engine's load is 7.6%

Figure 6 shows the main engine's consumption in 2 modes: fuel and LNG.

The fuel consumption has the same tendency than the engine's load. Globally, calculated values match well with the measurements. The steady-state RMSE of the engine's fuel consumption is 9.1%. Other factors than the engine's load prediction contribute to the error of the fuel consumption. A simulation using the measured load as an input was carried out, the RMSE fuel consumption of this model is 5.4%. This indicates that along with the prediction of the power, the engine model also needs to be improved for a better translation of power into fuel consumption.

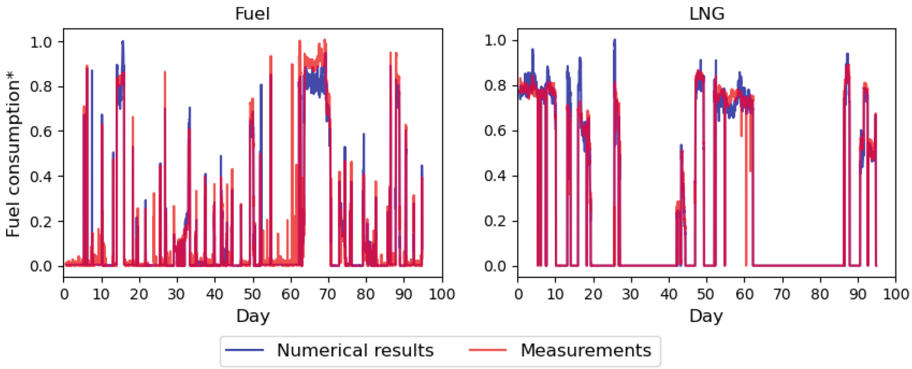

Fig. 6. Measured and calculated fuel consumption over time

4 Conclusion

This study proposed a new method for modeling the propulsion system of a vessel. The method combines a pre CFD-calculation for the environmental forces and a quasi-static model for the static equilibrium. This hybrid model makes it possible to simulate a long voyage (95 days in this study) within a reasonable numerical time. Globally, the model predicted well the tendency of the measured values. Steady-state RMSE of the engine's power and of the fuel consumption are 7.6% and 9.1% respectively.

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Ship Performance and Energy Consumption Evaluation Based on Modular Design Approach

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Abstract. The complexity of the shipbuilding process necessitates the development of a tailor-made innovative concept that is efficient in designing and building ships. To address this need, the Horizon 2020 European Union-funded NAVAIS research project was initiated (2018–2022). Among the various outcomes of this project, this paper focuses specifically on the development of partners' interaction-based modular fleets. To evaluate the behavior and performance of these modular fleets, an evaluation was conducted for both existing and future fleets, represented respectively by an electric ferry and a workboat. In order to facilitate these objectives, DS (Dassault Systèmes) provided a web-based multi-ecosystem platform called 3DExperience as a collaboration tool among partners. BV M&O (Bureau Veritas Marine & Offshore) subsequently utilized this platform to provide its in-house SEECAT (Ship Energy Efficiency Calculation and Analysis Tool) as a modular-based ship modelling and evaluation tool. These Model Based System Engineering (MBSE) approach can help comparing the performance of various ships, including their pollution levels, and identifying the best ship design for specific operational profiles, in a relatively short time.

Keywords: modular product · MBSE · design method · performance evaluation · energy consumption evaluation

1 Overview and Motivation

Ship is a highly complex, large-scale systems and expensive object that must be designed, built and maintained in a correct manner. The improvement of capability and capacity among the shipbuilders in recent decades competition creates enormous pressure to achieve design excellence and improve productivity. It is fundamental for any shipbuilder to manage successfully the relationships between design and customer requirements. Shipbuilders are expected to be able to engineer complex systems efficiently as well as evaluate and validate design options as early as possible in the cycle to avoid costly rework downstream [1].

To address these challenges, value-added and highly specialized vessels European shipbuilders must develop innovative concepts that are efficient to design and build.

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NAVAIS develops a platform-based modular product family approach supported by the 3DEXPERIENCE® platform. NAVAIS focusses on passenger & road ferries and multi-use workboats integrating sustainability in the design of the ships [2].

Shipbuilders are also expected to evaluate the performance and the emissions of the ship as early as possible in the cycle to avoid costly rework downstream. To do so, BV M&O developed a ship performance evaluation tool, called Ship Energy Efficiency Calculation and Analysis Tool (SEECAT). It consists of a library of various ship components developed in Modelica. The tool evaluates the ship performance and emissions such as CO_2, NO_x and SO_x for a realistic timewise description of the ship's operational profile [3], by simulating different energy flows and energy systems on board based on time domain, in a quasi-static manner and in a holistic approach. This tool is then called as SEECAT g1 [4]. The feature of this tool also aligns with the stringent ship air emission requirement, which was recently also emphasized by IMO, by the recent MEPC 377 (80) resolution regarding revised GHG strategy for shipping industry [5].

2 Methodology

NAVAIS uses system engineering approaches to develop the principles, procedures and a re-use component library for modular design and production. Each partner has access through 3DExperience; hence the design process will be more efficient, flexible and less-time consuming.

Another very important aspect is the evaluation of the performance of this modular vessel by using SEECAT. Nowadays, it is important to have a dynamic simulation tool, so that it captures a wider range of physical behavior, especially during transient period and also produces more detailed results. To address such a need, BV M&O redeveloped SEECAT during the NAVAIS project, which is then referred as SEECAT g2. Several features are considered in SEECAT g2, i.e., increased compatibility with Modelica language in general, capacity to simulate dynamic instead of quasi-static behavior, control logic was introduced, and the use of technical knowledge acquired from SEECAT g1.

3 Case Studies

3.1 Existing Fleet (Full Electric Double Ended Ferry)

The first case study was represented by two DAMEN's full electric double ended ferry: 6819 and 9819 ferries, for which the main principal dimensions are given in Table 1.

Since an electric vessel had never been developed using SEECAT g2, several components needed to be developed i.e., electric power system and energy storage systems. Once the electric power system and energy storage components were developed, the energy consumption onboard was assessed by a model developed in SEECAT g2, see Fig. 1a) and Fig. 1b). This vessel is equipped with four propellers and four motors, split equally at the fore and the aft, and a ship speed controller which receives the speed profile as a target. Concerning the energy source, this vessel is equipped with a battery that is charged with on shore charger during the loading-unloading process. The operational profile for both ferries is composed of two cycles of operation, with cruising speed of 12

Table 1. 6819 and 9819 Ferry principal's dimensions.

Variable	6819 Ferry	9819 Ferry
Length over all	71.70 m	99.30 m
Beam moulded	19.80 m	19.80 m
Beam over all	20.20 m	20.20 m
Depth at sides	4.63 m	4.63 m
Draught (max.)	2.90 m	2.90 m

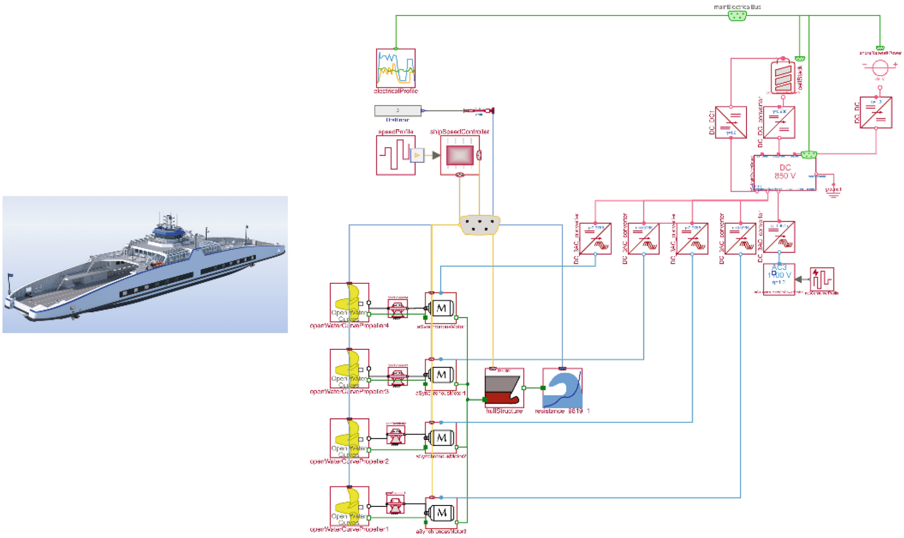

Fig. 1. **a)** Damen 6819 & 9819 ferries [6]. Image courtesy of Damen, reproduced with permission. **b)** System architecture in SEECAT g2.

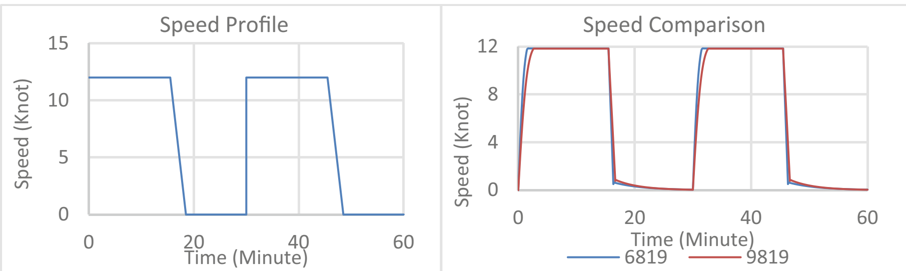

Fig. 2. **a)** The operational profile provided by DAMEN. **b)** The speed of 6819 and 9819 ferries upon its operational profile.

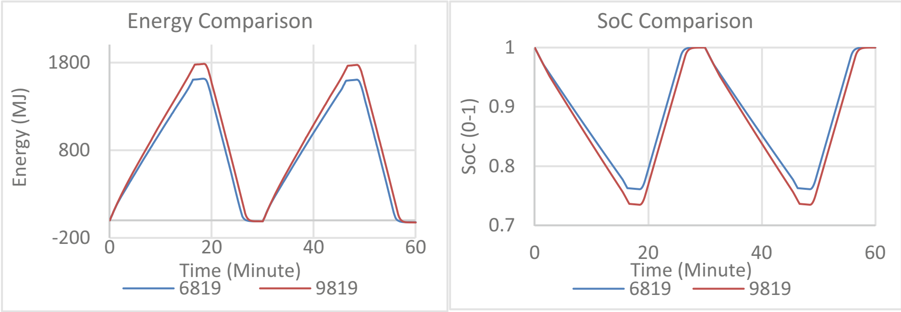

Fig. 3. **a)** The amount of consumed energy of 6819 and 9819 ferries. **b)** Battery SoC of 6819 and 9819 ferries upon its operational profile.

knots. One cycle of operation consists of 15.5 min of cruising time, 3 min of accelerating and decelerating time and 11.5 min of charging time.

Figure 2a) shows the operational profile of the ferries, while Fig. 2b) the speed for two ferries. Consequently, the amount of energy to operate those ships based on the operational profile above is depicted in Fig. 3a), with negative energy represents the charging period of the battery. An important aspect for electric ferry is the State of Charge (SoC) of the battery, in Fig. 3b), as this vessel does not have auxiliary energy source, the vessel's endurance only depends on the battery.

3.2 Future Fleet (Multi-use Workboat)

The aim of this case was to develop a platform-based workboat family for a wide range of customer demands. In this case, the components that were developed in SEECAT g2 are open water curve propellers and ship resistance as function of draft. This vessel is equipped with a couple of conventional diesel main engines and two propellers. As this ship is fueled by conventional fuel, SEECAT g2 was also used to evaluate the ship air emissions.

As the ship parameters were provided by DAMEN, 3DExperience was provided by DS as the platform to exchange the data. In this platform, SEECAT g2 library was deployed in 3DExperience, and DAMEN could then change or update the parameters on the ship system built in SEECAT g2. This process was done iteratively until the expected result was achieved, as depicted in Fig. 4.

In this workboat case, the operational profile was provided by DAMEN in the form of engine load time profile, as shown in Fig. 5a), and consequently, the resulting simulated speed is shown in Fig. 5b). It is worth noting that the measured speed graph appears steep on the full graph but is smooth when looking at the appropriate scale.

As this ship is fueled by conventional fuel, the associated fuel to perform such operational profile is shown in Fig. 6a), and consequently, the gas emissions emitted by the workboat is depicted in Fig. 6b).

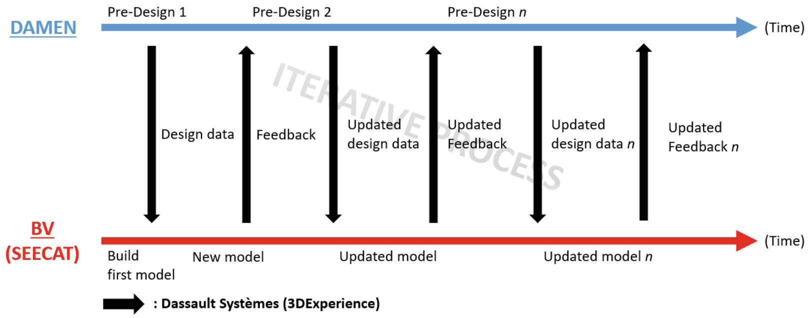

Fig. 4. Ship design iterative process between BV M&O and DAMEN, using 3DExperience.

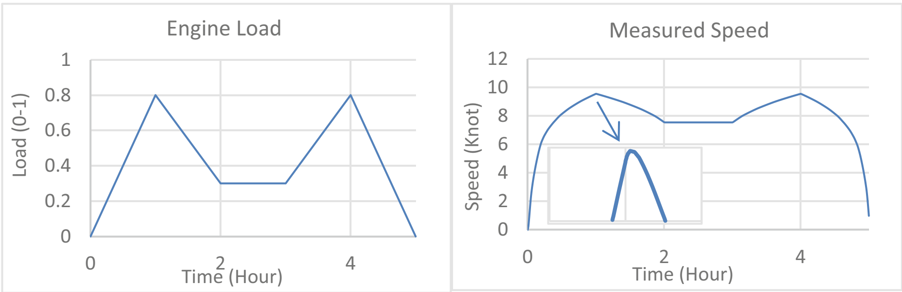

Fig. 5. **a)** Workboat operational profile i.e., engine load target. **b)** Workboat's resulting speed based on its operational profile.

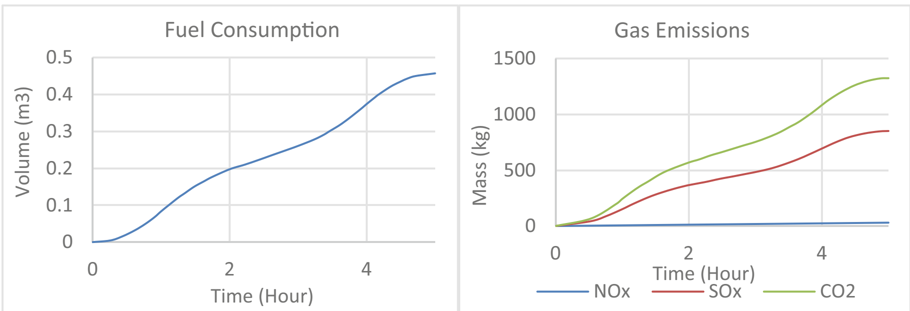

Fig. 6. **a)** Workboat's fuel consumption upon its operational profile. **b)** Workboat's emitted gas emissions.

4 Conclusion and Future Works

The presented method proved that by sharing components across a platform of vessels, less time-consuming design process could be achieved since every impacted organization has access to easily improve the ship design, evaluate its performance and the airborne emissions as well. These notions will help the shipbuilders to avoid costly rework downstream and have the possibility to choose the ship systems resulting in the lowest level of emission. In the context of ship performance evaluation, SEECAT g2 proved to be an essential tool. It is able to simulate the various energy systems of a ship. Newly developed models demonstrated the ability to simulate dynamic behaviors using control logic, so that, the results of simulations are now more robust and able to capture transient periods.

Acknowledgement. NAVAIS was the joint effort between 22 companies across Europe to develop a tailor-made innovative concept that is efficient in designing and building ships. The project has received funding from the European's Horizon 2020 research and innovation program, under contract number 769419.

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Developing Sulfide Based Solid State Battery with High Energy Density for Automotive Applications

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Abstract. The overall aim of the SUBLIME (Solid state sUlfide Based LI-MEtal batteries for EV applications) project is to respond to the further battery development challenges for Electric Vehicles and produce next-generation solid-state batteries (SSB) with extreme high energy density of up to 450 Wh/kg as compared to 250–280 Wh/kg for conventional cells to double the driving range of electrical vehicles.

The SUBLIME cell consists of a sulfide solid electrolyte (SE), Li metal anode and high nickel content cathode (NMC based). Up to now, we have overcome several challenges of this technology. The sulfide SE has been produced in kilogram scale with high ionic conductivity of 2.5 mS/cm at 25 °C and specific cathode and Li metal anode were developed for SSB application. The quality of the developed materials was confirmed in coin cell format, delivering a capacity of 195 mAh/g at 25 °C.

Next, we have been focusing on producing mono and multilayer pouch cells based on scalable process and optimizing the interfacial resistances between the cell components. For this purpose, coatings are applied on Li metal anode and cathode active material. The initial testing results of the pouch cells demonstrate the potential of this technology.

Keywords: Solid state battery · sulfide electrolyte · lithium anode · high energy density · high nickel content cathode · scalable process

1 Introduction

1.1 Future Market Development and Overview

Conventional batteries on the market are facing limitations in terms of safety, energy density and performance. Further development or even new technologies are required to realize high penetration and acceptance by the end users of electric vehicles (EVs).

In SSB, the flammable organic electrolyte is replaced with a SE that improves the safety, additionally, SE enables Li metal as anode which significantly improves the energy density.

Various types of SE such as oxides, polymers and sulfides exist and each one has its own advantages and challenges [1]. Oxides have high ionic conductivity and large

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electrochemical stability but are brittle with poor interface and mechanical properties that could crack during cycling of the cell. Polymers typically are stable versus Li metal anodes and are easy to integrate in SSB cells but are incompatible with high-voltage cathodes. Sulfide-based SE are produced from cheap reactants and could be simply upscaled. Additionally, they have high ionic conductivity and are ductile which allows easy integration in SSB. However, sulfides have narrow electrochemical stability, and coating is required to be applied in combination with high voltage cathode and Li anode. Several studies have shown that the stable interface with high voltage cathode could be achieved with proper coatings of cathode particles [2]. However, the main challenge of this technology is to make a stable interface with Li metal anode.

1.2 Targets of SUBLIME Project

Within the SUBLIME project, a novel high energy and power density SSB, based on a Ni-rich NMC cathode, Li metal anode and sulfide SE, is being developed. After optimization of the cells at lab-scale, the cell is being produced at a larger scale and the potential for scaling-up at the production level being evaluated. SUBLIME will focus on the so-called Generation 4b batteries with Li metal as an anode.

2 Achievements (During the Development Steps)

2.1 Material Development

In the first step of this project, the focus was on the development and upscaling of the SUBLIME cell components such as high nickel NMC cathode, sulfide SE and coatings for Li metal anode.

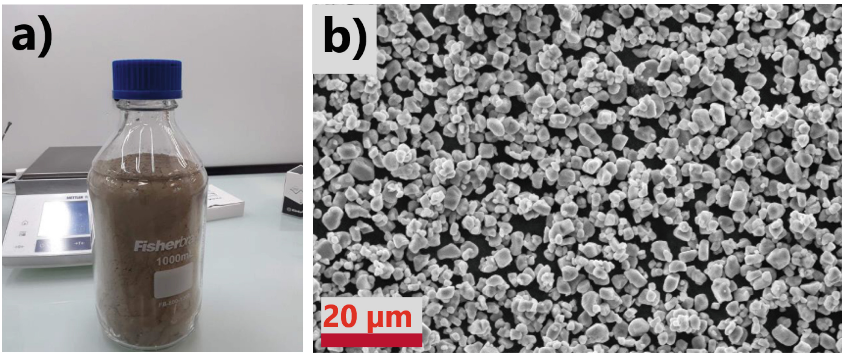

Fig. 1. Development and upscaling of a) SE (image courtesy of Syensqo, reproduced with permission) and b) Single crystalline NMC cathode developed in SUBLIME (image courtesy of Umicore, reproduced with permission).

Sulfide solid electrolyte with high purity was produced in kg scale (Fig. 1a) with high ionic conductivity of 2.4 mS/cm and activation energy of 0.406 eV. Additionally, single crystalline NMC 811 with D50–4 µm and special surface coating was developed.

In the next step, the performance of battery components was tested in a coin cell format with a pelletized cell to show the potentials and the challenges of the concept, see Fig. 2.

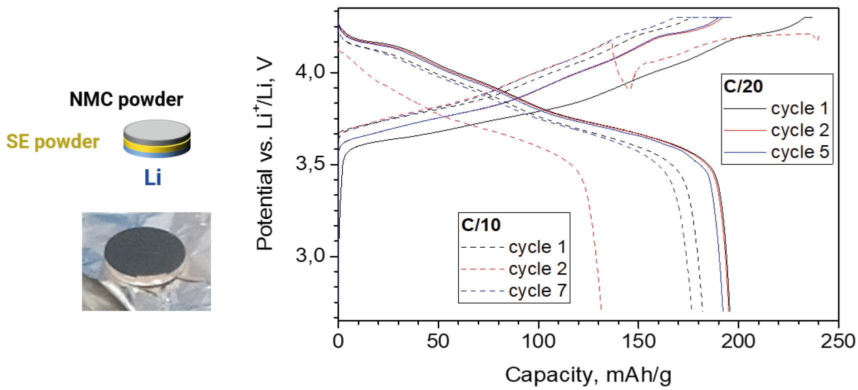

Fig. 2. SSB performance with NMC cathode, sulfide electrolyte (both in pelletized format) and Li metal anode (image courtesy of CIC energiGUNE, reproduced with permission).

The fabricated coin cell shows promising performance at C/20. A high reversible capacity of 195 mAh/g at RT was obtained. At higher C-rate of C/10, however, the cell starts to fail due to dendrite formation. Therefore, various coating strategies such as organic polymer coating, and inorganic coatings with atomic layer deposition (ALD) and thermal evaporation technique are considered to protect the Li anode. To illustrate the challenge, the Li metal anode used in the cell shown in Fig. 2 was not yet properly coated which resulted in Li-dendrite formation at higher C rates. However, new generations of coatings are under development and recently promising critical current density of 803 $\mu A/cm^2$ has been achieved for ALD coating of AlO_x on Li anode.

2.2 Electrode Development

The next step towards production of the larger pouch cells is the fabrication of SE and SE/cathode bilayer. For this purpose, several methods of dry processing, wet processing, drop cast processing and extrusion processing were considered. A detailed study was conducted for selecting a proper solvent and binder for the wet processing method [3, 4]. Figure 3 shows the SE/cathode bilayer that was prepared by wet processing with different binders and its cycling performance. The bilayer was punched, and coin cells were assembled to evaluate the performance of the layers. Li/In was used as a stable anode in contact with SE which allows the proper evaluation of bilayer performance without the challenges of Li anode. The assembled cells show stable performance with a capacity of approx. 87 mAh/g in the first cycle (Fig. 3). The lower capacity of this cell as compared to 195 mAh/g in the pelletized cell (Fig. 2) is due to addition of binder in SE and cathode electrodes that reduces the conductivity of the layers (Fig. 3).

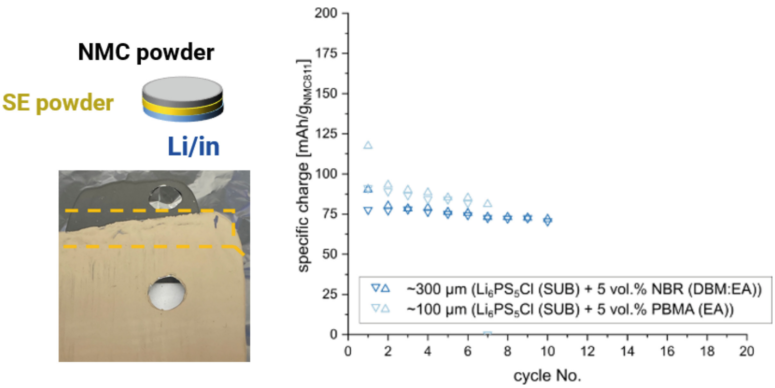

Fig. 3. Prepared SE/cathode bilayer and cycling stability (C/10) of the cast composite cathode by using different binders and electrolyte layer thicknesses (wet processing, image courtesy of AIT Austrian Institute Of Technology, reproduced with permission).

2.3 Larger Cell Development

Next, an extrusion process was used to make SE/cathode bilayer allowing the upscaling of the casting process as a crucial step for producing larger pouch cells.

For this purpose, an extensive study was conducted to optimize the processing parameters. As a result, the fabricated bilayer delivers a higher capacity of 112 mA/g for the first cycle in a coin cell format with Li/In anode (Fig. 4a) as compared to 85 mAh/g obtained in previous section by wet coating. The initial obtained capacity is improved but, the aging performance is worse, and optimization is in process. Additionally, monolayer pouch cells were fabricated based on these electrodes and their performances are presented in Fig. 4b,c.

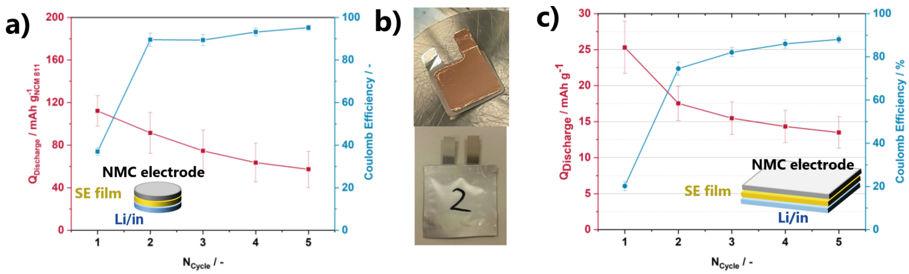

Fig. 4. a) Performance of the bilayers produced by extrusion process in coin cell format. b) monolayer pouch cells and c) performance of the bilayers produced by extrusion process in pouch cells (image courtesy of Fraunhofer institute IST and Technical University of Braunschweig, reproduced with permission).

The monolayer pouch cell showed a reduced discharge capacity of 25 mAh/g and the capacity loss is attributed to the changed compression and measurement parameters. While a pressure of 400 MPa can be applied during the fabrication process of 16 mm pelletized cell coin cell (Fig. 2), only a third of the pressure could be applied for pouch cells due to the larger area of these cells. Additionally, the pelletized cell was cycled under 25 MPa while the pouch cell was cycled under 10 MPa. The lower applied pressure result in electrodes with higher porosity and reduced electronic and ionic conductivity next to a less than optimal contact between the electrodes. Currently the optimization of the pouch cells is in progress and the effect of calendaring and stacking pressure on the performance of the cells are under investigation. The first batch of pouch cells were produced with Li/In anode with the aim to focus on the performance of the cathode and SE layers and optimize their fabrication. The second batch of pouch cells will be produced with Li anode and upscaling continues toward multiplayer 10 Ah pouch cell.

2.4 Modeling of the Cell Technology

Several numerical Ab Initio Molecular Dynamics (AIMD) simulations have been performed on SUBLIME materials. The AIMD simulations suggested different coatings on Li anode to prevent the decomposition of SE, among them Li_2Sn_5 exhibits the best-predicted performance (Fig. 5) [5].

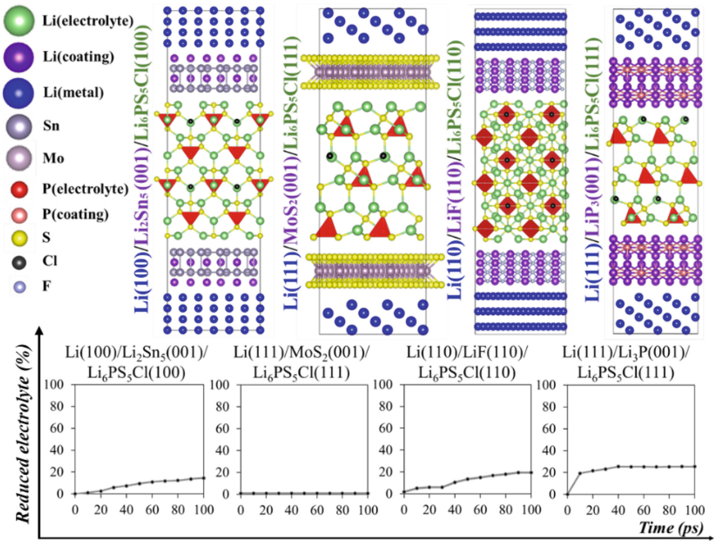

Fig. 5. AIMD simulations of Li/coating/Li_6PS_5Cl (image courtesy of CIC energiGUNE, reproduced with permission, The AIMD simulations were performed using the Vienna Ab Initio Simulation Package -VASP)

In addition to the AIMD simulations, Pseudo-Two-Dimensional (P2D) and Pseudo-Four-Dimensional (P4D) models were developed (at coin cell level) to predict the electrochemical performance of the cell. Figure 6 shows that the developed models are in well agreement with the experimental data and will be used to predict the lifetime degradation of SSB. These models will be next implemented in the battery management system.

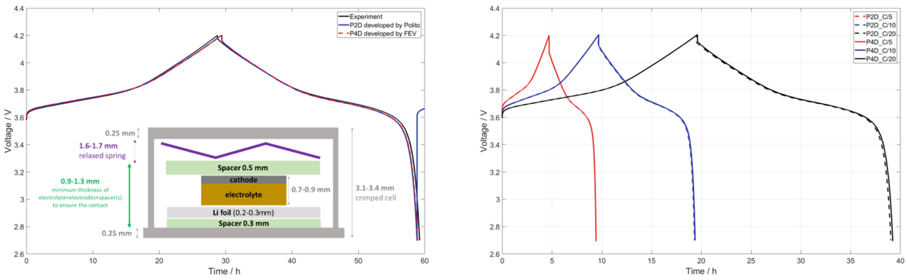

Fig. 6. P2D and P4D models developed to predict the cycling data (image courtesy of Polytechnic University of Turin and FEV Europe Gmbh, reproduced with permission).

3 Outlook and Conclusions

In SUBLIME, the goal is to develop next generation SSB with sulfide SE, high nickel NMC cathode and Li anode. Sulfide SE with high ionic conductivity and NMC cathode with special coatings were developed and produced in pilot scales. The coatings of Li anodes were thoroughly investigated and recently a stable coating is developed which will be used in the next generation of cells. In addition, the bilayer cathode/SE electrode was successfully fabricated by an extrusion process as a scalable method and the first batch of pouch cells were produced. AIMD simulation suggested stable coatings for Li anode and the P2D and P4D models were developed (at coin cell level) to fit the electrochemical performance of the cell. In the next steps, the fabrication of pouch cells with lithium anode are in process and the effect of various parameters such as calendaring and stack pressure on the performance of the SSB will be investigated.

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Silicon-Based Lithium-Ion Battery Cell Material Tests, Supported by Finite-Element Model Simulations

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https://www.virtual-vehicle.at/, https://greenspeed-project.eu/

Abstract. The greenSPEED projects ambition is to create a safe, long-lived, high-capacity battery cell, while reducing the carbon footprint and environmental impact during its production. This will open the opportunity for cheaper and "greener" mobile electric applications.

Focusing on the development of a new generation of lithium (Li) ion battery cells, containing specially treated copper and aluminium foils as current collectors and promising silicon-based anode material. Tests are carried out on pouch cells and cylindrical cells (21700) and are supported by finite element model (FEM) simulations

Tensile tests are done for the different cell components to obtain material parameters for FEM simulations. The specific material models will be used to assemble a cell model to propose improvements for cell design and the overall mechanical properties of the cell.

The newly developed battery cells will additionally be tested for their expansion behaviour under varying conditions and the data will be used to parameterise an expansion model which will be used for the cell simulations. The combination of material specific models and expansion model will lead to simulations which give insight in the mechanical behaviour of the battery cell and stress distribution during charge and discharge. This toolchain will increase the development speed and provides a modular framework for further investigations.

Keywords: Battery · FEM · Silicon · Simulation · Lithium Ion Battery · Copper Foil · Aluminium Foil

1 Introduction

Battery production nowadays is demanding very high energy densities as well as safe and environmentally friendly production which are both non trivial restrictions. The search for the right material is often limited by the experience with

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and availability of products. A component that is often neglected is the current collector foil for both electrodes. Copper (Cu) as the dominant choice for the anode current collector foil and Aluminum (Al) as the preferred choice as cathode current collector foil can both be prepared in various ways spanning different pre-coatings, thicknesses, temperatures and other surface treatments.

Silicon in its pure form has an extremely attractive theoretical capacity of about 4200 mAh/g [1]. Its impact on Li-ion battery industry, so far, was nevertheless negligible. One of the main reasons for that is the drastic expansion, about 300% [2], of silicon while intercalating Li, which introduces mechanical stress in the cell, leading to crumbling of the electrode and therefore to moderate cycle stability in Li-ion battery cells. The expansion can be reduced by using silicon-based compounds while also reducing the capacity of the material compared to pure silicon. The right choice in current collector, however, will improve cycle stability without negative impact on capacity.

In this work, we focus on specially treated foils for this specific battery cell generation, using a pure silicon anode.

The material characterisation is important for the follow up simulations for single cells and cell design. Especially, the predicted behaviour of the anode for the upcoming cylindrical cell production is of importance.

State of the art material tests are used and measurement standards for Cu and Al foils have been tested. The production supporting FEM simulations are done in commercially available finite element solver LS-DYNA [4]. The mechanical cell model in addition includes an electrical model using Randles elements [3] (EM_RANDLES_SOLID) as well as a recently added state of charge dependent expansion model MAT_ADD_SOC_EXPANSION_TITLE.

2 Material and Battery Tests

An example of a stress-strain curve obtained from a tensile test is given in Fig. 1, this test was carried out on Al foil sample as it can be used in lithium ion batteries as cathode current collector. A set of parameters, from now on called material model, can be extracted from this experiment including yield strength, elasticity modulus and plastic load curve. Yield strength and elasticity modulus can be obtained by applying the 0.2% offset rule [6]. The tests are repeated at least 3 times to allow statistic evaluation of the material parameters. The pure Si anode changes its volume during insertion and extraction of Li-ions. This behaviour is crucial for further cell design. Therefore, experimental data is needed to have appropriate theoretical expansion models. The cell expansion can be measured during formation as well as constant current/constant voltage cycling, which will also provide cell performance information needed to setup the electrical simulation. The used experimental setup is described in detail in the paper of Kargl et al. [7] We apply a pressure of 0.5MPa during the experiment and can relate cell expansion to the SOC (State of Charge) of the battery. This experiment has been done with 3 cells to obtain an average cell behaviour.

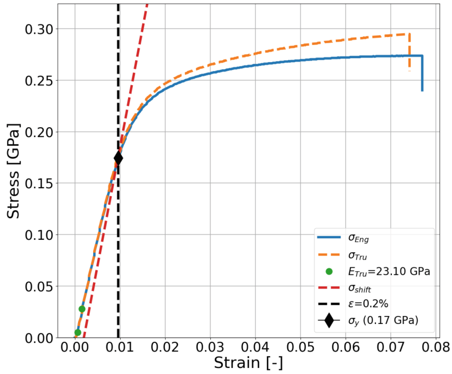

Fig. 1. Example stress σ versus strain result for Al. engineering values in blue, true stress and strain in dashed orange, 0.2% offset method line in dashed red with results in dashed black, yield point as black rhombus. Source: Authors

3 Battery and Material Models

The main impact on the cell predictions, outside of the material model, will be given by the definition of simulation parameters and key influences on the cell, as defined as follows. In this paper we apply a constant current profile on Randles elements defined by experimentally obtained parameters. The current profile charges the cell from 20% to 80% SOC at a constant current. Furthermore, expansion of the anode is included, since Si is known to expand up to 300% while intercalating Li.

The material model for each experiment is optimized with LS-OPT [5] to obtain a better match with experimental data, including simulation approximations. An example for comparison of the extracted material model and the optimized material model to the corresponding measurement is given in Fig. 2. Due to the simplifications in our model and the extraction method, the experimentally obtained values do not automatically match the simulation results. The initial material model is not able to reproduce the experimental data well in our simulations, whereas a good agreement is reached after a few optimization iterations. The optimized parameters for each material are used to create an average material model which will be used in the simulations. The parameterised cell component models are assembled to a bi-layer cell model which is used for the simulations. The stack of the pouch cell includes separators at the top and bottom as well as between the cathode and anodes (two single-side coated anodes and a double-side coated cathode in the centre). Each electrode has an extension of the current collector to allow electrical contact, called tab. A pouch foil envelops the stack and is sealed on the edges while allowing cathode tab and anode tab to stick out. Due to the layout of the pouch cell, two Randle elements are included in the cell, representing the two “layers” of the bi-layer cell, with each “layer” corresponding to one anode active material side and one cathode active material side. The thickness change of the silicon anode is much higher

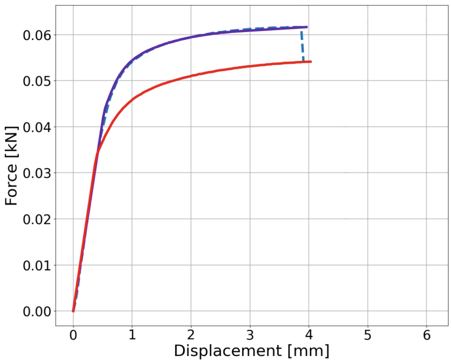

Fig. 2. Simulation data with experimentally extracted model (red), optimized simulation data (purple) and experimental data (dashed blue). Source: Authors

compared to the cathode, which is why the cathode contribution is neglected in the model. This allows to obtain the anode-expansion introduced stress from simulation, an important parameter for cell design and development.

4 Results and Discussion

Figure 3 shows the resulting displacement as response to the anode expansion. One can see that the pouch foil in this case is lifted together with the underlying stack, which is the result for the induced stress seen in Fig. 4. The electrode tabs are mainly displaced close to the main stack body. This is true for all tabs that are above the very first anode, since the anode is responsible for expansion in this cell. The second anode tab, which is located close to the top of the stack, is

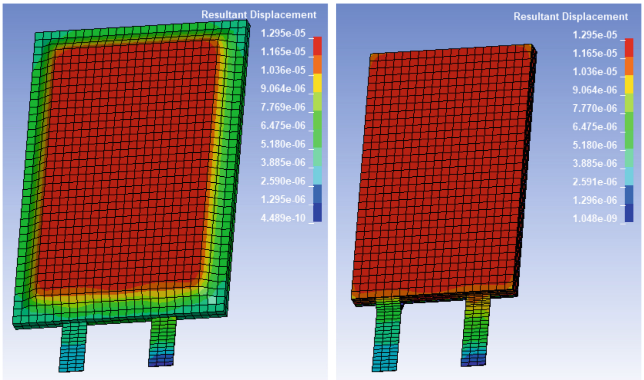

Fig. 3. Simulation results of the displacement of mesh nodes, left: the full pouch cell and right: the stack inside the pouch cell. This figure was created using LS-PrePost. Source: Authors

displaced due to expansion and forces the first anode tab, close to the bottom of the stack, also to be displaced since they are connected to each other. In other words the second anode tab is slowly pushed away from the first.

Also the cathode tab, here a single one shown to the right of the pouch cell, is displaced close to the stack due to anode expansion, which might become a problem since the pouch foil covering the tabs will fixate the tabs.

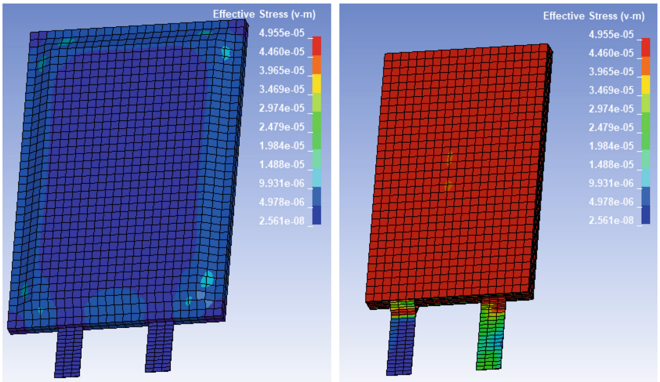

Fig. 4. Simulation results of the stress distribution inside left: full bi-layer pouch cell and right: stack inside the pouch cell. This figure was created using LS-PrePost. Source: Authors

These effects might lead to failure if the pouch swells further or for multi-layer pouch cells, which would lead to higher absolute expansion. Figure 4 shows the stress distribution inside the pouch cell. While the pouch foil itself is not affected too much by anode expansion, we can see that the stress increases in the cell stack as well as on the tabs. The connected anode tab shows maximum stress on the interface between the two tabs since they are pushed apart, whereas the single cathode tab exhibits the highest stress close to the stack.

Overall, we present an approach of battery cell simulations, starting from simple material analysis resulting in a coupled electro-mechanical FEM of a bi-layer pouch cell. The obtained data can be used for defining regions of interest in cell design as well as areas of potential failure in extensive cell use and up-scaling.

In future simulations, this approach will also be used for 21700 cells. The combination of Si anodes in 21700 cells will need support on simulation side to get insight in the pressure and stress distribution inside the cell which is not feasible experimentally as well as locations of possible areas of failure/interest. As one example, the jelly roll in cylindrical cells is assembled by a rolling process. During this step, considerable stresses are introduced in the jelly roll which can be analysed using an adapted version of the presented mechanical model. In a subsequent step, the anode expansion can be simulated to further investigate expansion-induced stresses and will lead to a better understanding of design limitations.

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Socioeconomic Assessment of Electric Road Systems (ERS)

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Abstract. Electric Road Systems (ERS) are defined as a set of subsystems that enable power transfer from the road to a vehicle in motion and have the potential to reduce our dependence on fossil fuels, reduce greenhouse gas emissions, mitigate air pollutants, and minimize noise pollution in urban areas. Therefore, to maximize the social benefit and reduce the opportunity cost, specific methods must be designed to conduct an evaluation from a socio-economic perspective, contribute to the efficient allocation of public resources, analyze sustainability in the transport sector and offer reliable information based on profitability indicators to decision makers in selecting the implementation of ERS. The objective of this paper is to propose a methodology that may be useful for government institutions, entities, and agencies to evaluate the socio-economic feasibility of ERS to ensure an efficient allocation of public resources and move towards the decarbonization of the transport sector in a long-term horizon.

Keywords: Electric Road Systems · socioeconomic · assessment

1 Background

ERS are defined as a set of subsystems that enables power transfer from the road to a vehicle in motion. It can be made through different types of technology: conductive (road-bound, road-side and overhead lines) and inductive (dynamic wireless charging). ERS represent a groundbreaking technology, marking a notable departure from the conventional refuelling process at traditional gas stations. ERS introduces an innovative solution that has the potential to electrify not only long-distance heavy-duty road transport but also buses and, potentially, passenger cars—eliminating the need for large batteries in the process. ERS have the potential to reduce our reliance on fossil fuels, diminish greenhouse gas emissions, mitigate air pollutants, and minimize noise pollution in urban areas. Simultaneously, ERS stands to significantly enhance energy efficiency within the transportation sector. Consequently, ERS is rapidly gaining prominence in contemporary discussions surrounding sustainable transportation strategies.

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2 Research Objective

The objective of this paper is to propose a methodology that may be useful for entities and agencies to evaluate the socio-economic feasibility of ERS to ensure an efficient allocation of public resources. To achieve these objectives, tools are shown that describe the main components that a cost-benefit analysis of this type of project must contain. The internal evaluation model captures, from a socio-economic perspective, the elements involved in the decision to implement a road investment project with inductive charging technology.

3 Methodology

The methodology for the socioeconomic evaluation of an ERS requires certain steps that are explained below:

3.1 Step 1. Analysis of the Scenario Without ERS

The objective of this analysis is to describe the problems that give rise to the project. It requires knowing the existing supply and demand. The offer is represented by the physical and geometric characteristics of the current infrastructure. While demand refers to the Annual Average Daily Traffic (AADT) or number of average vehicles that travel daily on the road. The latter should be analyzed by congestion hourly distribution and vehicle type. It also looks at how supply and demand interact on each section of the relevant road network, which is reflected in the speed, travel time and cost incurred by road users. The latter is known as Generalized Travel Cost (GTC) and is integrated by the cost of operating the vehicles (VOC) plus the cost of passenger travel time (TTC). As a result of the interaction between supply and demand, the problem to be solved is identified and described along with the externalities involved.

3.2 Step 2. Analysis of the Scenario with ERS

It is done in a similar way as in the scenario without ERS. The difference is that in this case the supply is given by the characteristics of the project (Fig. 1) (Haddad 2022). It also analyzes how supply and demand interact, which in the same way, is reflected in speed, travel time and GTC.

The situation with project considers the implementation of an ERS through the installation of inductive wireless power transmitters in one lane in each direction to provide electric charging to heavy vehicles. To achieve the objective, it is necessary to carry out an analysis of the subsystems that make up the ERS (CoERS, 2019):

- **Electricity supply ($\mathbf{E_{supply}}$).** It is divided into three components:
  - **Transmission.** It includes how electrical energy flows from generation sources over long distances (i.e., grid interconnection subsystem).
  - **Distribution.** It includes how energy flows through the network to the energy transfer subsystem (i.e., load subsystem).

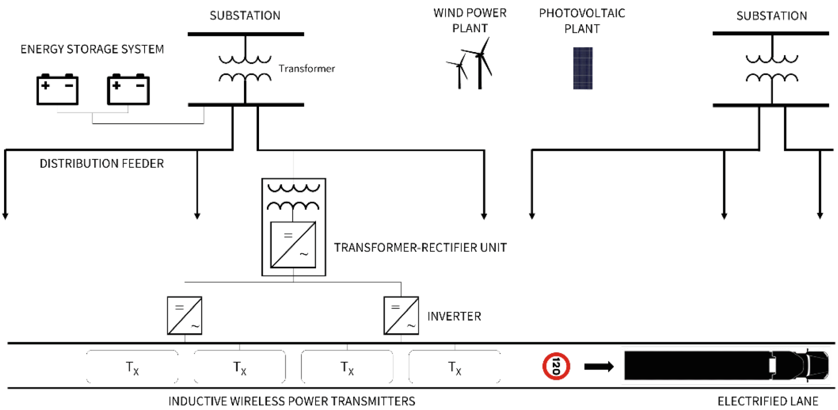

Fig. 1. Proposed architecture of an ERS project

- **Management components.** It includes the control, operation, operation and balancing of energy in the subsystem. Also consider the source of generation.

- Road infrastructure ($R_{infrastructure}$). It is divided into three components:
  - **Pavement.** It includes the structural body, the marking or road markings (horizontal and vertical signage) and the electric road installation method.
  - **Barriers.** Includes safety and acoustic protection components.
  - **Auxiliary components.** It includes traffic signs and other necessary roadside components.

- **Power transfer ($P_{transfer}$).** It is divided into three components:
  - **Road energy transfer.** It includes on-road equipment that is responsible for vehicle detection and power transfer from the road.
  - **Vehicular energy transfer.** It controls the safe activation and operation of an energy receiver and measures the energy transferred after recognition.
  - **Control.** Supervises the transfer of energy and the operation of the subsystem.

- **Vehicle (V).** It includes the necessary component that converts the power of the energy transfer subsystem into vehicle propulsion or energy storage. A control component provides user information, fleet management and vehicle positioning.
- **Operation (O).** It controls the overall system's energy management, provides user information, and handles payment, billing, access control, and road lanes based on vehicle identification.

3.3 Step 3. Identification, Quantification and Valuation of Costs

After having identified the situation without and with ERS, Fig. 2 includes a framework with the identification of costs associated with an ERS.

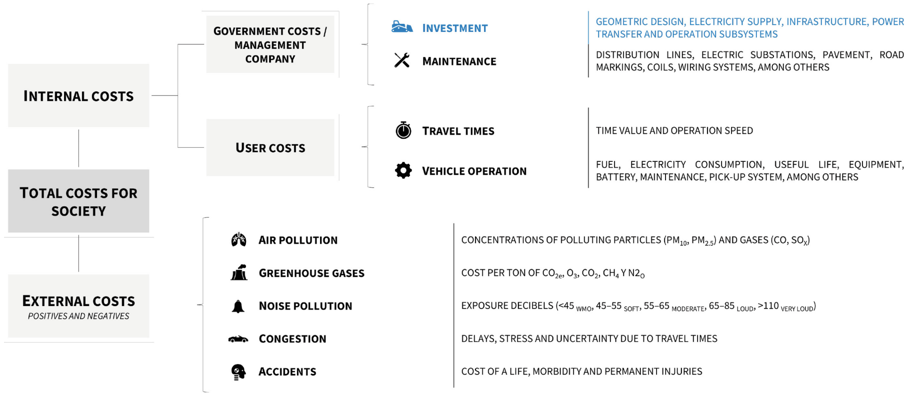

Fig. 2. Identification of costs associated with an ERS

INTERNAL COSTS

- **Investment cost.** It includes the costs associated with the following subsystems: electricity supply subsystems, road infrastructure, power transfer and operation. The investment cost can be calculated according to the expression:

$$INV = \sum C_{Subsystems}$$

INV	investment cost
E_{suply}	cost of the power supply subsystem (e.g., distribution lines, electrical substations, storage systems, power inverters, rectification units)
$R_{infrastructure}$	cost of the road infrastructure subsystem (e.g., pavement, beacon works, civil works)
$P_{transfer}$	cost of the power transfer subsystem (e.g., coils, cabling networks and interconnection systems)
O	cost of the operation subsystem

- **Maintenance.** It includes the costs associated with the periodic work that must be carried out for the proper functioning of the ERS.
- **Generalized travel costs.** It includes vehicle operating costs (VOC) and travel time costs (TTC) and measures in monetary terms the cost to the user of driving through the ERS.

GTC IN THE SCENARIO WITHOUT ERS

Must be calculated by type of vehicle for each section, direction, and time of congestion according to the expression:

$$GTC_{i,j,k} = VOC_{i,j,k} + TTC_{i,j,k}$$

i	can be light vehicle (A), bus (B) or articulated truck (C)
j	section of the road
k	congestion schedule and day.
$GTC_{i,j,k}$	overall travel cost calculated for vehicle type *i* in the section *j* and congestion schedule *k*
$VOC_{i,j,k}$	vehicle operating cost or average variable cost of using a vehicle type *i* in the section *j* and congestion schedule *k*
$TTC_{i,j,k}$	cost per travel time of passengers traveling in the vehicle type *i* in the section *j* and congestion schedule *k*

The VOC measures in monetary terms the cost to the user to drive on a road. Its calculation includes direct costs per time (amortization and financing of the vehicle, driving staff, insurance, and tax costs) and per kilometer (fuel, consumption of urea solution, tires, maintenance, repairs, allowances, and tolls) and indirect costs (ACOTRAM 2018). The TTC represents the value, in monetary terms, of the travel time of the people traveling in each type of vehicle *i*. It is given by the unit value of people's time (€/h) multiplied by the travel time in hours and by the number of passengers.

GTC IN THE SCENARIO WITH ERS

The GTC calculation for the scenario with ERS uses the same expression as in the current situation, however, the estimate of the VOC varies since it considers the investment and the cost of adaptation or equipment of an electric vehicle (EV), the price of electricity, the consumption of electrical energy (Taljegard 2020) and the loss of capacity due to batteries and on-board systems. The annual costs that vary with respect to the situation without ERS are amortization since the acquisition value of the EV considers the elements necessary for its adaptation such as the pick-up system, the electric motor, and the battery. Likewise, the fuel calculation differs since the price of electricity and electrical consumption for an EV must be considered.

EXTERNAL COSTS

For the monetization of the external costs the Handbook on the External Costs of Transports can be used (European Comission 2019).

- **Air pollution.** It includes the costs associated to health effects (inhalation of air pollutants such as particulate matter PM_{10}, $PM_{2.5}$ and nitrogen oxides NO_X), crop losses (O_3, VOC and other acidic air pollutants like SO_2 and NO_X can damage agricultural crops), material and construction damage (contamination of building surfaces through particles and dust and damage to the facades and materials of buildings due to corrosion processes), loss of biodiversity (the most important damages are acidification of soil, rainfall, and water and eutrophication of ecosystems).

- **Greenhouse gases.** It includes the costs associated with all the effects of global warming, such as sea level rise, biodiversity loss, water management problems, increasingly frequent extreme weather events and crop failures. The impacts of transport on global warming are mainly caused by CO_2, N_2O and CH_4.
- **Noise.** It includes costs associated with unwanted sounds of varying duration, intensity or other quality that cause physical or psychological harm to humans (CE Delft 2011). Exposure to noise has several negative health effects due to prolonged and frequent exposure to transport noise. The health endpoints for which important evidence is available are ischemic heart disease, stroke, dementia, hypertension, and discomfort (Defra 2005).
- **Congestion.** The average travel cost borne by road users is based on the product of the time value, which can be assumed constant for all road users, and the average travel time. There are two approaches to estimating the costs of road congestion: delays (value of travel time lost relative to a free-flowing situation) and loss of efficiency (seek of the optimal economic solution).
- **Accidents.** It includes the social costs of road accidents that are not covered by risk-oriented insurance premiums (costs that are not covered by insurance are external).

It should be considered that in the category of internal costs, the investment is estimated on a single occasion for the implementation of the ERS (in blue in Fig. 2). On the other hand, the costs of maintenance, vehicle operation, and travel times, together with external costs must be calculated for both scenarios (situation without and with project).

3.4 Step 4. Identification, Quantification and Valuation of Benefits

Regarding the benefits, these are obtained from the comparison of the user costs (GTC) and external costs between the scenario without and with ERS. The most significant benefits are expected in environmental terms, as the comparison of air pollution and greenhouse gas emissions costs are lower in the ERS scenario derived from the difference in vehicle technology (EV vs. diesel vehicle). Regarding GTC, the VOC between a diesel vehicle and an EV is similar (the differences that exist between acquisition and fuel costs of a diesel vehicle are compensated in terms of maintenance and electric cost of an EV throughout its useful life). However, the TTC could represent savings since vehicles in the situation with ERS do not need to stop to recharge the battery (electrical supply represents a lower cost than fueling the vehicles with diesel). The investment is considered as a negative impact for the evaluation process. As a result, the analysis performs a flow of benefits over the life of the project which is key for decision-makers in selecting ERS implementation.

3.5 Step 5. Project Evaluation

Finally, to evaluate the social profitability, the net flows for each year of the evaluation horizon are calculated considering the distribution of the AADT by congestion schedule and type of vehicle. These net flows are the difference among the scenarios proposed. Based on this, the indicators of Net Present Value (NPV), Internal Rate of Return (IRR) and Immediate Rate of Return are calculated. A sensitivity analysis should also be carried out in which the behavior of the profitability indicators to the change in the relevant variables of the project, such as the amount of the investment or the projected demand, is observed.

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Advances in Steel FSW for Transport Applications

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Abstract. Friction stir welding (FSW) is a solid-state joining process that gives welds with excellent mechanical properties. The drive towards electrification has seen FSW adopted by the automotive sector for the fabrication of lightweight aluminium car bodies and battery assemblies. Element Six utilised their expertise in high performance, abrasion and temperature resistant materials to develop a FSW tool for steel and this was trialled at TWI where welding techniques were developed to allow welds to be made both in air and under water. A rigorous, independent assessment of weld quality was undertaken by the Technical University of Delft (TUD) and publications and dissemination resulting from this work has identified a number of potential other applications across the wider transport sector.

Keywords: Friction Stir Welding · inland waterways · rail · hydrogen transport · cryogenic service

1 Introduction

Friction stir welding (FSW) was invented and developed for fabricating difficult to weld metals such as aluminium in the 1990's by The Welding Institute (TWI). FSW is a solid-state joining process that gives high strength, tough, fatigue resistant welds with minimal distortion and so was quickly adopted by the aerospace, rail and shipbuilding sectors for building aircraft, fast ferries and high-speed railway locomotives and carriages. More latterly, the drive towards electrification has seen FSW adopted by the automotive sector too for the fabrication of lightweight aluminium car bodies and battery assemblies. Transferring the technology to the fabrication of steel was always seen as desirable but was frustrated for almost three decades by the difficulty in developing a FSW tool that can withstand the higher temperatures and forces associated with welding steel.

In 2013 the EU Project HILDA (High Integrity Low Distortion Assembly) identified a viable steel FSW tool as a key technology that would be required to maintain the competitiveness of the EU shipbuilding sector. Project RESURGAM, led by the European Welding Federation (EWF) and with partners representing the EU shipbuilding sector, developed in response to that challenge.

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2 Friction Stir Welding

Friction stir welding is a solid-state welding process and as such has a number of technical advantages over more tradition welding techniques that rely first on melting and then on resolidifying the metal of components to be joined. The process of friction stir welding is very simple:

- A rotating tool is used to generate frictional heating which softens the material to be welded;
- The tool is then traversed along the joint line, mechanically stirring the two components together.

3 Tool Development

The development of tools sufficiently strong to stir steel, and to be chemically inert to the steel itself at the high temperatures required to soften it, means that introducing FSW to steel is a challenging undertaking. Few materials retain adequate strength, toughness and abrasion resistance to stir steel at the required temperature (around 900 to 1,000 °C) and of those that do, the problems of steel's high chemical reactivity results in rapid tool wear as the hot steel effectively alloys with and dissolves the tool.

Consortium member Element Six is a world leader in the development of materials for use in extreme environments, particularly at high temperatures and under extremely abrasive conditions. Using that expertise, Element Six developed a Polycrystalline Cubic Boron Nitride (PCBN) based tool for welding steel of 6 mm and 12 mm thickness. Work is ongoing to refine the design of the tools and the materials used to manufacture them, the intent being to enhance tool life, reduce too cost and increase the thickness of steel that can be welded.

Historically, other materials like refractory metal tools made from tungsten (W) or (W-Re) and Polycrystalline Cubic Boron Nitride (PCBN) have been successful in welding steel. However, low tool life and high cost in combination with lack of consistency in performance makes commercial application difficult. As part of RESURGAM project Element Six has developed and produced advanced PCBN tools to address some of the challenges that were seen before. PCBN is produced through a High-Pressure High Temperature sintering technique, where CBN is mixed with carefully designed binder containing high temperature refractory materials. The mix was sintered under a pressure between 4–6 GPa and temperature between 1200–1600 °C. Tools were scaled up through design modification and keeping synthesis conditions similar to produce tools with similar thermal and mechanical properties and consistent properties helped achieving reproducible results in welding different thicknesses.

4 Weld Properties

Friction stir welds in steel are performed over the transformation temperature range of steel and so, with careful choice of the welding parameters, the scope exists to tailor the microstructure and thus properties of the welds made towards particular service conditions such as high strength, toughness, cryogenic service or fatigue resistance.

The resulting weld has a fine grained, forged microstructure rather than the large, columnar grained, cast microstructure typical of a traditional fusion weld and thus has excellent mechanical properties (strength, toughness, ductility) along with good resistance to fatigue and corrosion. The process is automated and also has considerable Health and Safety benefits.

Hardness testing has shown that the hardness of the welded material exceeds that of the parent metal, reaching values as high as 350HV2. The main driver behind the increased hardness is the reduced grain size. However, for certain combinations of welding parameters, the thermal profile in time and space results in the formation of harder steel phases. These results are confirmed by tensile tests which fail outside the welded material when no large defects are present in the weld. Tensile test pieces that were notched to force the failure to take place in the weld rather than the parent metal were failing at about 750 MPa, thus giving a measure of the weld metal strength. The welds have impact toughness between 80 and 120 J, depending on the welding parameters. The impact toughness is significantly increased compared to the base metal value of approximately 25 J, even when the welded material was much harder.

Fatigue performance of defect free welds have fatigue strength exceeding that of base material at FAT170, with similar slope of $m = 5$. Cracks initiate at the weld toe and grow perpendicular to the loading through the HAZ and base material. Fatigue strength of welds that contain defects is lower at FAT120, however, still higher than the design FAT class of FAT90. Rather than decreasing, which is typical for welds with defects, the slope increases reaching values as high as $m = 9$, meaning that fatigue performance at higher stresses is poor.

5 Process Economics

Resurgam has shown that all the benefits of the FSW process already proven in aluminium apply to steel, producing strong, tough welds in a wide range of steels – including dissimilar grades and those traditionally considered difficult to weld by other processes. However, whereas in aluminium friction stir welding is usually lower cost than other processes, in steel the process is generally considered to be more expensive than existing techniques due to the higher cost of tools for steel FSW. But is it really?

Friction stir welding is typically performed as a simple square butt weld, eliminating the need to machine specialist edge preparations such as V or J groves. A finished friction stir weld typically has a smooth, spatter free surface, reducing or eliminating the need for post weld grinding and cleaning in many applications.

An obvious cost saving associated with the elimination of filler wire is the cost of the wire itself. However, it is often forgotten, or not even realised, that the major cost of the filler wire lies in its storage and administration. The wire should be kept in humidity controlled storage to mitigate against problems with moisture absorption and potential hydrogen embrittlement of the welds made.

The low temperatures and lack of melting associated with friction stir welding reduce the heat input to the weld zone, frequently resulting in fabrications with minimal distortion and so eliminating the need for subsequent straightening operations.

Conventional arc welding processes become costly, less effective and potentially hazardous when employed under water. At shallow depths divers can be employed, with all their associated cost and safety implications, and at greater depths it is necessary to use robotic welding systems or hyperbaric chambers. Friction stir welding can be performed at any depth using virtually the same equipment as is used for welding in air, and with far fewer problems such as hydrogen embrittlement arising from ingress of moisture into the weld zone as this is sealed off from the water by the embedded tool.

If one considers the true costs of welding fabrication, then FSW, an automated, mechanical process that produces high quality, tough, strong, fatigue resistant, autogenous welds 24 h per day may be cost competitive in many applications. FSW reduces or even eliminates many of the costs identified above. Consider just a few of these.

- How much is spent on NDT, QC and rectification during other welding processes?
- How much is spent on purchasing, storing, controlling and disposal of flux in arcs processes?
- How much is spent on welder training and qualification with other welding processes?

6 The Route to Industrialisation

A key feature of the RESURGAM project has been the aim to develop an industrialisation strategy alongside the technical innovations needed to bring about the transfer of FSW technology from aluminium to steel. This was initially targeted on two specific applications in the shipbuilding sector, the modular fabrication of new ships and the at sea repair of existing ships. In addition, the consortium was also keen to explore the possibility of expanding the technique into other sectors. In parallel with this, effort has also been put into the regulatory requirements that will need to be satisfied if steel FSW is to become a widely used technique, with TWI leading discussions with classification societies such as Lloyd's Register in order to facilitate the approval of the process for shipbuilding, and the creation of an ISO Working Group to develop an ISO standard for FSW of steel for more general use.

6.1 Modular Manufacture

Many ships are now built in a modular fashion from stiffened panels, these then being built up into blocks which are in turn built up to form the majority of the inner structure of the ship. An alternative technique for the manufacture of stiffened panels, maximising the benefits of friction stir welding, is by moving to the Integrally Stiffened Panel concept developed as part of Resurgam. The ISP replaces the two fillet welds with a single butt weld to join a wrought plate spacer to a rolled T section. This Integrally Stiffened Panel (ISP) concept and a small demonstration panel made by the technique is presented in Fig. 1. The friction stir welded ISP results in a fully forged structure that is potentially stronger, more fatigue resistant and less distorted than an arc welded equivalent. In summary, the ISP replaces two arc fillet welds with one FSW butt weld, gives a fully forged structure, uses commodity items, permits easier inspection, reduces distortion.

In order to make the adoption of FSW easier, consortium member Stirweld has developed a friction stir welding head that can be retrofitted to an existing CNC milling machine. This is a much lower cost approach than buying a bespoke friction stir welding machine. Stirweld was created in 2017, based on a simple purpose: Make FSW accessible to any company already equipped with a CNC milling machine. Stirweld created an FSW head that can reach forging forces up to 25 kN. A Stirweld FSW head turns the position control of the CNC into a force control, and therefore protects the spindle of the CNC, and ensures a very high-quality weld. Of course, one of the top advantages of using an FSW head instead of buying a specific machine is the way much lower investment needed at first. And, furthermore, you can easily unmount the head, and use the regular functions of your CNC.

R & D is always ongoing at Stirweld, so many add-ons have been developed, such as temperature measurement system, milling add-on, automatic head drop off…etc. Based on this, Stirweld has designed and manufactured an FSW head, made to weld steel and meant to be used on huge CNC machines such as in drydock shipyards. Its forging force goes up to 50 kN, and its cooling system has been entirely re-designed to deal with high temperature reached during steel welding.

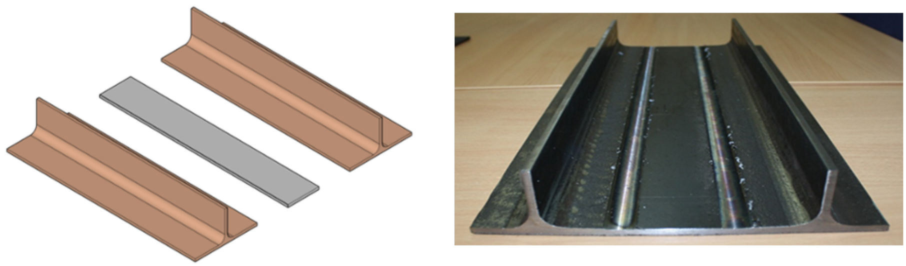

Fig. 1. Integrally Stiffened Plate demonstration fabricated by friction stir butt welding two rolled T sections to a steel plate. Source: Authors.

6.2 At Sea Repair

Resurgam looks to eliminate the costs and dangers associated with underwater repair by developing a small robot that can be deployed over the side of a ship whilst it is in harbour loading or unloading routine cargo. The weld repair robot, design and manufactured by Forth Engineering, operates using the validated weld parameters confirmed by TWI at their test facility. To which it exerts a 4000 kg plunge force, 246 Nm torque at 200 RPM (Ramped down from 800 RPM), driven at a linear speed of 260 mm/min, found to be a strong combination of output parameters when looking to install a mild steel repair patch of 4mm thickness, using a 6 m FSW tool supplied by Element 6.

The robot enacts its operational requirements by utilising a modular design, consisting of a compact FSW Head, linear drive track and tied together with a robust support body. Using 2 hydraulic motors to transmit the respective required welding spindle and linear drive speeds and 2 hydraulic cylinders to provide the requisite plunge force. As well as retractable rare earth magnet clamping assemblies, to locate itself onto the site of any prospective ship. All of which are connected through and remotely controlled by an intelligent hydraulic valve chest, programmed to drive the robot at the exact specified set points. The robot prototype has now been fully manufactured and has entered its testing phase, which will conduct numerous dry welds and subsequent wet weld tests. To not only confirm the suitability of the design's integrity, but also checks the designed equipment can also in fact delivery the required weld operational outputs, and ultimately create a Friction Stir Weld of acceptable quality that could be used in real life applications. And finally, develop a plan of residual work required to take this robot from a prototype, to a commercialised product that can start to be used in the field and realising its benefits (Fig. 2).

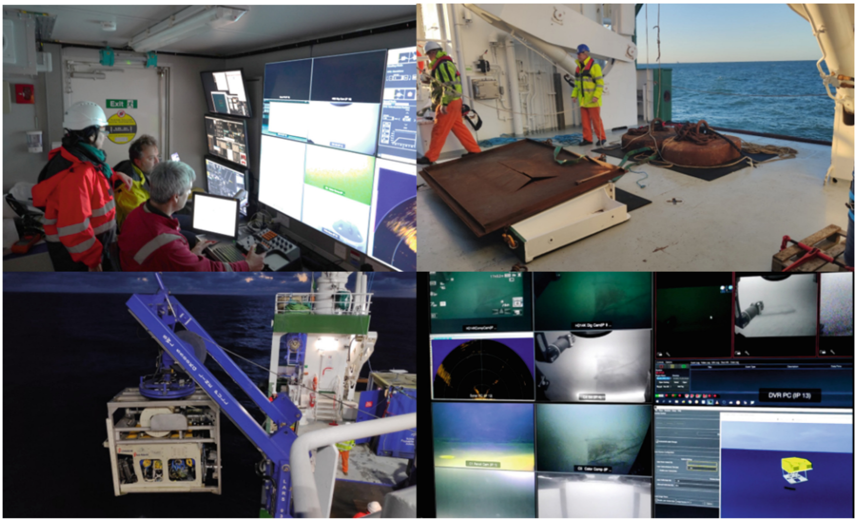

Fig. 2. Use of an ROV at sea to undertake scanning of an area of a ship to be repaired. Source: Authors.

6.3 Other Sector Applications

During the course of the RESURGAM project, particularly as the dissemination efforts began to report on the achievements being made, enquiries were received about friction stir welding of steel from other sectors, all interested in discovering if the advances being made in the shipbuilding application could be applied in their market sectors. These are briefly outlined below.

Civil Engineering: Many applications in civil engineering utilise stiffened panels or very similar fabrications, for example bridge decks, floors for multi-storey steel framed buildings and supporting or reinforcing structures for concrete fabrications. In many cases, these would be ideal candidates for manufacture by friction stir.

Defence: Many applications in the defence sector use complex alloy steels that are far from easy to weld by conventional arc welding techniques, frequently requiring pre- and post-weld heat treatment and the use of specialist fillers and shielding gases. Friction stir welding is less susceptible to problems caused by alloy composition, thus reducing or eliminating many such issues, and has already been utilised for aluminium armoured vehicles. In addition, friction stir welding's ability to generate very strong, tough microstructures, and now to do so in hard materials such as steel, offers considerable promise for enhanced performance in applications where ballistic impact and blast loading may be a concern.

Nuclear: The nuclear sector provides a number of potential applications for FSW of steel. The sealing of copper canisters for radioactive waste by FSW has already been approved by the Swedish nuclear authorities and the use of the process to seal cheaper stainless or mild steel canisters is under investigation in the USA, Sweden, Switzerland and Canada.

Oxide dispersion strengthened (ODS) alloys, including steels, have been developed for applications where good mechanical properties are required at elevated temperatures, for example in steam plant, nuclear plant and gas turbines. Fusion welding of these alloys, however, is detrimental to their properties and thus there is limited scope to fabricate large components from ODS materials. Friction stir welding, being a solid state process, offers an opportunity to overcome this difficulty.

Stainless steels, often 304L and 316, are widely used in the nuclear industry. Friction stir welding has the ability to produce high integrity welds in these steels and, being a solid state process, is far less susceptible to problems associated with hydrogen entering and embrittling the weld metal than conventional fusion processes. Hydrogen embrittlement is a very significant issue in the nuclear industry, especially in areas subjected to irradiation. Feng et alia demonstrated that, even with no attempt to optimise the FSW process, the maximum helium bubble size in a friction stir weld is only about 27% of a gas tungsten arc weld of comparable size.

Pipeline Construction and Repair: Pipelines continue to represent one of the most efficient ways of transporting bulk fluids over long distances, both on land and subsea. Many pipelines are still fabricated by hand welding, or the use of semi-automated systems. Replacing these techniques with an automated friction stir welding solution would potentially bring considerable benefits, both technical and in terms of Health and Safety where pipelines are being constructed in inhospitable environments. Orbital FSW systems could make single pass girth welds in thin-walled pipes (up to 12 mm wall thickness), and pipes of wall thickness up to 25 mm could be welded by using a simultaneous internal and external welding system, each reacting its tool forces against the other system.

Steel FSW, in combination with technologies such as the robotic FSWBOT system can be deployed to carry out internal repairs on pipelines, even when they are live. FSWBOT has shown that it is possible to weld under oil, thus avoiding penalties for non-delivery of oil whilst a pipeline is having a corroded area repaired. A similar consideration may apply to public utility pipelines such as water or district heating, it potentially being possible to repair these without closing them down or digging up the road network to access them.

Pipeline Refurbishment and Re-purposing: A further area where FSW of steel has attracted interest is for the refurbishment of existing pipelines for the transport of new products for example CO2 in sequestration schemes, or the transport of hydrogen (sometimes in the form of ammonia) as part of the drive towards a hydrogen economy. Both these applications require weld joints that are tough at low temperatures and which, ideally do not have a large columnar grain structure that can provide a rapid diffusion path for small gas molecules. A robotic FSW system could travel through old pipelines to refurbish the welds, generating a tough, fine-grained microstructure at the existing girth welds in order to improve their fitness for purpose and allow existing infrastructure to be re-used for new products.

Welding of Coated or Clad Pipes: As friction stir welding is a solid-state process, i.e. one in which no melting takes place, it is also suited for the welding of coated or clad pipes. Careful choice of tool design and process parameters will allow a weld to be made without the coating or cladding being melted and dissolved into the underlying steel, thus maintaining the integrity and preserving the protective function of the layer.

7 Conclusions

In summary, it can be stated that Resurgam has shown that steel can be friction stir welded using a range of specialist tools developed by Element Six, and that these tools consistently produce defect free, strong, tough welds with low distortion and good fatigue resistance. The tools have a life of 60 m of weld in 6mm thick steel and a life of 30 m in 12 mm thick steel. Welds have been made in air and under water, in square butt and lap geometries A range of carbon steels have been welded, including S355, S460 and S690. Stainless steel grades 304 and 316 have been welded, and stainless steels (316 and Duplex 2205) have been welded to carbon steel (S355).

Resurgam has therefore successfully demonstrated that not only can the technique of friction stir welding and all its benefits be transferred from aluminium to steel, but has also developed the tools and proof of concept equipment that will be required for the industrial adoption of the process. The objectives of achieving this for the transport sector have been met, and the process is now seeing widespread interest from many other markets, providing Europe with potentially world leading opportunities to enhance its manufacturing capabilities.

Estimating the Energy Demand of Electric Vehicles for Charging Infrastructure Planning

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Abstract. To ensure that adequate charging infrastructure is available where it is needed, accurately estimating the spatial distribution of energy demand is essential. In this paper, we present a data-driven approach for estimating the demand for electric vehicle charging stations. For destination charging demand, we leverage publicly available sociodemographic data, a POI database, and mobility statistics, including daily trip rates, modal share, and trip length distributions. En-route charging demand is estimated using highway traffic count data. We account for EV battery capacity, maximum mileage, and driver charging behavior. Statistical parameters related to the EV fleet (penetration rate, home-charging percentage) are considered to adapt estimates for various scenarios. We present an interactive web-based GIS tool that displays energy demand densities for passenger and freight transport via heat maps, demand generated at POI, and demand along highways. By combining estimated demand with existing charging station data, the tool calculates unmet residual demand, facilitating the planning of future charging infrastructure. Our data-driven approach provides a valuable tool for estimating electric vehicle charging station demand, offering insights into spatial energy demand distribution and supporting future infrastructure planning efforts. Notably, this approach relies solely on readily available data, enabling immediate use in practice and easy adaptability to various regions.

Keywords: electric vehicles · energy demand · charging infrastructure

List of Abbreviations

EV	electric vehicle
LCVs	light commercial vehicles
PCs	passenger cars
POI	point-of-interest
SoC	state-of-charge

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1 Introduction

A fast and smooth transition to electric vehicles (EVs) requires an accelerated rollout of the charging infrastructure. The EV Charging Infrastructure Masterplan for the EU-27 envisions a requirement of about 6.8 million public chargers for passenger cars (PCs), 0.7 million for light commercial vehicles (LCVs), and 0.1 million for trucks and buses to be deployed across Europe by 2030 [1]. According to the European Green Deal, a charging station should be available every 60 kilometres on major highways [2]. To ensure that adequate charging infrastructure is available where it is needed, accurately estimating the spatial distribution of energy demand is essential.

Several existing studies on optimizing charging infrastructure [3,4] address the trip assignment of EVs, taking into account limited range. In these studies, EVs must adhere to distance constraints and plan detours to charging stations (en-route charging) within their travel routes. Other studies [5–8] explicitly examine the interdependencies between transportation and energy infrastructure, exploring approaches for the coordinated planning of both systems. Some recent studies also employ machine learning algorithms to estimate charging demand. For example, [9] use a Multi-graph convolutional Neural Network to predict charging demand based on traffic flow. The results are then used to optimize the charging infrastructure with a Cournot game model considering multiple competing service providers. An overview of further previous studies on data-driven estimation of EV charging demand is provided in [10].

In this paper, we present an interactive decision support tool for assisted manual planning of new charging infrastructure based on projected demand and taking into account the demand already covered by existing or planned charging locations. We focus on estimating current charging demand through simplified modeling of traffic demand using readily available data. This makes the presented approach easily transferable to different regions. We consider two different types of demands identified in [11]: *destination charging* and *en-route charging*. In our analysis we assume that the daily range of a private car is sufficient for everyday trips, eliminating the need for on-road charging along lower-level road networks. Instead, charging occurs directly at the destination points. En-route charging becomes relevant for longer journeys, typically taking place on highways and major roads. Consequently, we estimate en-route charging demand only for trips using the higher-level road network.

For the destination charging demand, our approach utilizes publicly available sociodemographic data, mobility statistics such as daily trip rates by purpose, and a point-of-interest (POI) database to estimate the traffic generated at trip origins and destinations. Origins and destinations are matched according to trip length distributions collected in the latest nationwide mobility survey [12]. For the en-route charging demand, we consider the traffic count data on highways provided by the road operator. Taking into account the battery capacity and maximum mileage of electric vehicles, as well as the charging behavior of drivers, we estimate the demand for en-route charging at each highway ramp. For both types of demands, we consider the statistical parameters on the electric vehicle fleet (EV penetration rate, home-charging percentage) to scale and adapt our estimates for different scenarios. The results are presented as an interactive web-based Geographic Information System tool with multiple map layers [13]. They show the energy demand densities for passenger and freight transport in the form of heat maps, demand generated at POIs, and demand along highways. By combining the estimated demand with data on the locations and capacities of existing charging stations, the tool calculates the unmet residual demand to support the planning of new charging infrastructure in the future.

The remainder of this paper is organized as follows: Sect. 2 outlines the methodology used to estimate charging demand, while Sect. 3 introduces the web-tool that was developed as a result. Section 4 concludes this paper.

2 Methodology and Modelling

We use different methods for assessing the different demands for the energy demand. Following cases are considered:

– En-route charging
– Destination-charging

For en-route charging we distinguish between passenger transport and goods transport. For destination-charging, we only consider passenger transport since goods transport will most likely start or end in a compound area, therefore there is no demand for public chargers.

2.1 En-route Charging

For En-route charging we estimate the demand based on traffic counting data on highways and country roads in Steiermark.

Highways: Traffic counting data for highways is publicly available from ASFINAG[1], the national road authority in Austria. From the data, we know the number of cars and truck that pass each counting point per year. Highway segments directly at counting points are assigned the indicated throughput. For other segments the throughput is interpolated between the counting points. We make the reasonable assumption that charging on the highway itself is not possible, but only at (potential) chargers at highway service stations or at highway exits. They are assigned the energy demand of nearest highway segments. The left side of Fig. 1 shows an example where counting points and highway exits are located nearby the city of Graz.

For each vehicle passing a service station or highway exit, we estimate the likelihood that it requires en-route charging if it is on a long-distance trip. Without taking into account the exact origin and destination, we assume that when a car is below 20% state-of-charge (SoC), it might want to charge to 80% SoC. In the EV Database[2], the 75th percentile of passenger cars in 2023 has a battery

[1] www.asfinag.at/verkehr-sicherheit/verkehrszahlung/.
[2] www.ev-database.org/cheatsheet/range-electric-car.

capacity of 86 kWh and a reach of 440 km. By applying the operating range of 20% – 80% SoC, it will recharge every 264 km–352 km. If a charging station is located every 60 km (goal of "Fit for 55" by the European Commission[3]), the probability results in 9.7% per car with a charging demand of around 51.6 kWh – 68.8 kWh if it is on a long-distance trip. According to Österreich Unterwegs, the percentage of car trips by Austrians that exceed 50 km is 5.7% in rural areas. Furthermore, we assume that foreign cars on Austrian highways (around 43%) are on long-distance trips. Therefore, we conclude that around 46% of the cars on the highway are on a long-distance trip that potentially requires en-route charging, resulting that 4.5% of cars passing a potential charging station requires charging.

For electric trucks, the performance data is very sparse. From the usability point of view, we believe that it should at least have the performance of a Tesla Semi in order to be broadly adopted. Therefore we assume a battery capacity of 850 kWh and a reach of 800 km. By applying the same logic, it will recharge every 480 km–640 km, and since nearly 100% of the trucks on highways are on a long-trip, a truck passing by a charging station that requires en-route charging is around 5.3%.

Country Roads: For the country roads we use the counting data from TomTom. Similar to the highway counting points, they provide the number of cars that for each road segment per year. We make the assumption that potential charging stations will be built in or nearby cities in the municipalities, but not in the middle of nowhere. Therefore, we assign the charging demand for each road segment to the nearby towns. The right side of Fig. 1 shows an example for the country roads and the towns in an rural area.

Since the number of vehicles on a long-distance trip is much lower on a country road compared to highways, the probability of cars requiring en-route charging is much lower. Since no further information is available, we estimated them to be 1/5 of the cars on the highway.

Fig. 1. (a) Highway (green segments), counting points (small purple circles), and highway exits (large red circles). (b) country roads with traffic volume (purple and red segments), and town centers (red circles).

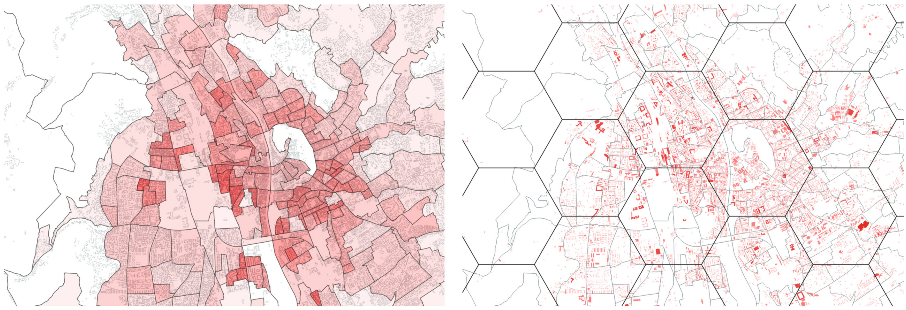
[3] www.consilium.europa.eu/en/policies/green-deal/.

2.2 Destination Charging

The charging demand at trip destinations is estimated using a procedure that includes the following steps:

1. **Trip Generation**: Estimation of the number of car trips from each origin point.
2. **Trip Distribution**: Allocation of generated trips to destinations.
3. **Car Travel Performance per Destination**: Estimation of total driven car kilometers based on the number and length of trips to each destination.
4. **Identification of Charging Demand per Destination** based on car travel performance and the share of battery-electric vehicles.

The estimation of generated traffic is based on publicly available census data, residential building data [14], and traffic statistics from the latest nationwide mobility survey [12]. The trip origins are aggregated in a hexagon grid with a radius of 1km. We start the calculation with translating the population figures from census tracts to the hexagon cells. This is accomplished by geographically overlaying the census tracts with residential building data to determine for each census tract the average population count per square meter of residential land use. The population count in the hexagon cells was then computed by overlaying the residential buildings with the hexagon grid and aggregating the population within the grid cells (Fig. 2).



(a) (b)

Fig. 2. Translation of the population numbers from census tracts to residential buildings (a) and from residential buildings to a hexagon grid.

For the calculation of generated trips, we differentiate shopping trips (subdivided into daily, medium-term, and long-term needs), leisure trips, errands, and visits. Trips to work have been excluded from this study, based on the assumption that private charging stations exist at the workplace, which are not considered in this study. However, the methodology presented here could be extended in a similar fashion to also include commuter routes. For the generation of trips originating in a cell we consider the spatial types "peripheral," "central," and "metropolitan". These spatial types are defined by the mobility survey based on administrative districts, but can easily be transferred to the hexagon cells.

The number of generated car trips for each combination of hexagon cell c and trip purpose p is determined using the following formula:

$$O_{c,p} = R_c \times N_{t(c)} \times F_p \times C_{p,t(c)}. \tag{1}$$

Here, R_c represents the population count in cell c, $t(c)$ denotes the spatial type of cell c, N_t stands for the average number of trips per person for spatial type t, F_p represents the relative proportion of trip purpose p, and $C_{p,t}$ indicates the share of car trips with purpose p and spatial type t. The parameter values for N_t, F_p, and $C_{p,t}$ were adopted from the mobility survey (see Table 1).

Table 1. Mobility figures adopted from the mobility survey [12].

	peripher	central	metropolitan	
number of trips per person	**2.7**	**2.8**	**2.9**	
shopping	0.4	0.4	0.5	**16%**
leisure	0.4	0.4	0.4	**15%**
errands	0.4	0.4	0.4	**13%**
visits	0.2	0.2	0.2	**8%**
proportion of car trips	**56%**	**51%**	**39%**	
shopping	54%	49%	37%	**45%**
leisure	36%	33%	25%	**30%**
errands	56%	51%	39%	**47%**
visits	54%	49%	37%	**45%**
number of car trips per person				
shopping	0.23	0.22	0.17	
leisure	0.14	0.14	0.11	
errands	0.20	0.19	0.15	
visits	0.12	0.11	0.09	

For assigning the trips generated at the origins to the destinations, we use a POI database. The POIs are linked to trip purposes and assigned weights. The weighting for "Shopping" POIs is determined based on the sales area; for "Leisure" and "Errands," weighting is based on customer ratings included in the POI database, giving more weight to popular POIs. Residential buildings are used as POIs for "Visits" trips and weighted with the previously estimated number of people residing in the building. The weight of a POI d for trip purpose p is denoted as $W_{d,p}$.

Another factor in the distribution is the travel distance $l_{o,d}$ between origin o and destination d. We approximate the travel distance distribution $F_L(l)$ based on the distance frequencies of car trips reported in the mobility survey. The estimated number of trips from source cell o to POI d is given by

$$M_{o,d} = O_{o,p} \times 1/Z \times W_{d,p} \times F_L(l_{o,d}). \tag{2}$$

Here, $Z = \sum_d W_{d,p} \times F_L(l_{o,d})$ acts as a normalization factor ensuring that $O_{o,p} = \sum_d M_{o,d}$.

The total car travel volume for a destination d is then given by

$$V_d = \sum_o M_{o,d} \times l_{o,d}. \tag{3}$$

In our estimation, we equate the charging demand at a destination with the energy consumption derived from the distance traveled. We acknowledge that the amount of energy charged at a destination doesn't always correspond directly to the energy consumed during the journey to that point. The actual charging dynamics can vary due to factors like state of charge at departure and anticipated return charging. However, estimating top-up charging based on energy consumed on the outbound trip simplifies the estimation process and provides a practical approximation.

We consider the distance traveled to be the main driver of energy consumption. While other variables might also influence energy usage, such as driving conditions and vehicle efficiency, the energy-distance relationship is a central aspect of electric vehicle operation and provides a sensible estimate. We therefore use the total car travel volume V_d, the proportion p_{ev} of electrically powered cars, and the average energy consumption rate $\bar{E}$ of an electric car to estimate the Destination Charging demand

$$D_d = V_d \times p_{ev} \times \bar{E}. \tag{4}$$

The penetration rate p_{ev} and consumption rate $\bar{E}$ are adjustable scenario parameters. Allocating charging demand to specific POIs enables spatial aggregation and a direct comparison with the current charging infrastructure. This allows for the calculation of any remaining unmet demand.

3 Results and Discussion

Destination and en-route charging demand was estimated for the entire federal state of Styria. Styria covers a total area of $16,400\,\text{km}^2$ and has a population of 1.2 million in 2023. Most residents and trip destinations are concentrated in the capital city, Graz. In Styria, Graz has the "metropolitan" spatial type, the Graz-Umgebung district is "central," and the remaining districts are "peripheral".

The results of the charging demand analysis are presented in an interactive web-tool with multiple map layers. Detailed information about the generated demand at POIs and along highways is provided. The locations, types (fast or slow charging), and capacities of the existing charging infrastructure are visualized. The web-tool is shown in Fig. 3.

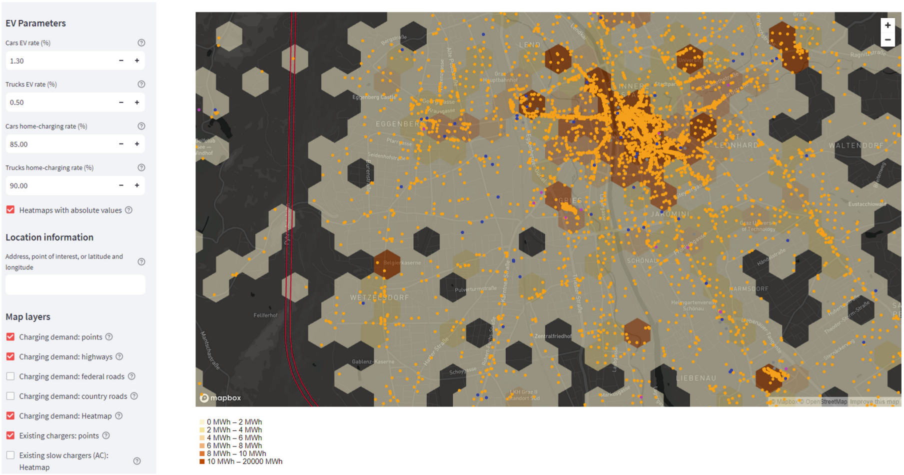
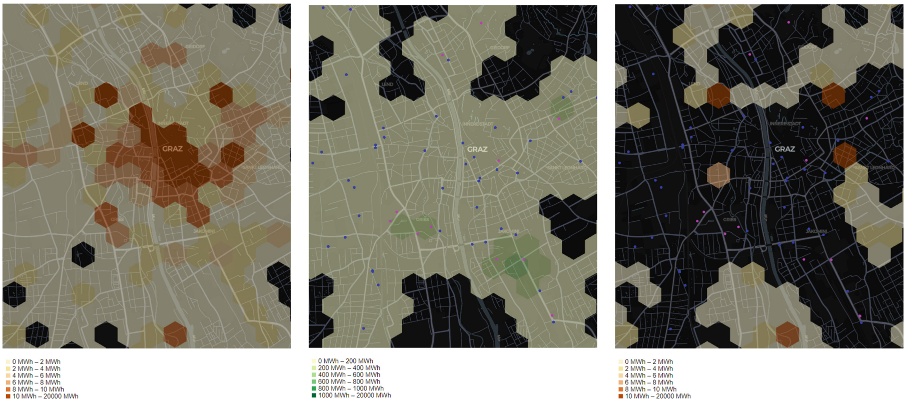


Fig. 3. Example for the tool, showing the area around Graz. Left is the input panel and right is the map area. On the map, the POIs are shown as yellow points, existing chargers as blue/purple points, the highway as red lines, and the heatmap for the energy demand as hexagons.



(a) (b) (c)

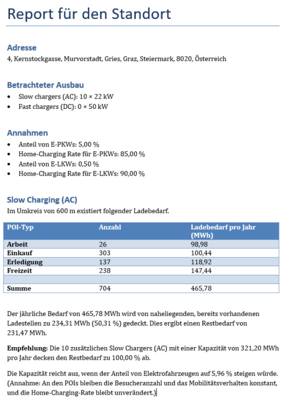
Fig. 4. Heat map visualization for Graz: Current charging demand at an EV penetration rate of 1.3% (a), coverage of the existing chargers (b), and the unmet demand (c).

One of the main results is the aggregated charging demand displayed as heat maps. The user can select and visualize the estimated current demand and/or the coverage of existing charging stations. By combining the current demand with the current coverage, the tool calculates and visualizes the unmet residual demand to support the planning of new charging infrastructure in the future. An example is shown in Fig. 4.

Users can change basic parameters such as EV penetration rate and home-charging percentage to forecast the future demand. Users also can selectively analyze potential new locations and generate automated reports. These reports depict the demand for fast and slow charging stations in the vicinity of the analyzed location and show the distances to the POIs and highway ramps where the demand was allocated. The demand is compared to the capacities of the existing infrastructure to provide a decision-making basis for the establishment of new infrastructure. Finally, it is also possible to simulate new infrastructure at a location selected by the user. After configuring the type and capacity of the new infrastructure, it is incorporated into the calculation and visualization of the covered and uncovered charging demand. This is shown in Fig. 5. The report on the right side of Fig. 5 indicates the following:

For the location "Kernstockgasse 4, Graz" there are 704 nearby POIs with an estimated charging demand of 465.78 MWh per year at an EV penetration rate of 5%. Existing chargers nearby covers 234.31 MWh (50.31%). If 10 new chargers at 22 kW are installed, they produce an additional 321.2 MWh per year and cover the demand. This capacity would be sufficient if the EV penetration rate would rise to 5.96%.

(d) (e)



Report für den Standort

Adresse

4, Kernstockgasse, Murvorstadt, Gries, Graz, Steiermark, 8020, Österreich

Betrachteter Ausbau

- Slow chargers (AC): 10 × 22 kW
- Fast chargers (DC): 0 × 50 kW

Annahmen

- Anteil von E-PKWs: 5,00 %
- Home-Charging Rate für E-PKWs: 85,00 %
- Anteil von E-LKWs: 0,50 %
- Home-Charging Rate für E-LKWs: 90,00 %

Slow Charging (AC)

Im Umkreis von 600 m existiert folgender Ladebedarf.

POI-Typ	Anzahl	Ladebedarf pro Jahr (MWh)
Arbeit	26	98,98
Einkauf	303	100,44
Erledigung	137	118,92
Freizeit	238	147,44
Summe	704	465,78

Der jährliche Bedarf von 465,78 MWh wird von naheliegenden, bereits vorhandenen Ladestellen zu 234,31 MWh (50,31 %) gedeckt. Dies ergibt einen Restbedarf von 231,47 MWh.

Empfehlung: Die 10 zusätzlichen Slow Chargers (AC) mit einer Kapazität von 321,20 MWh pro Jahr decken den Restbedarf zu 100,00 % ab.

Die Kapazität reicht aus, wenn der Anteil von Elektrofahrzeugen auf 5,96 % steigen würde. (Annahme: An den POIs bleiben die Besucheranzahl und das Mobilitätsverhalten konstant, und die Home-Charging-Rate bleibt unverändert.)

(f)

Fig. 5. Heat map visualization for Graz: The increase of unmet demand when the EV penetration rate rises from 1.3% to 5% (d), simulated new location for 10 new chargers to cover the demand (e), and the report for the new location (f).

4 Conclusion

We presented a methodology and an interactive tool for comprehensive analysis of EV charging demand, utilizing a data-driven approach that integrates various data sources and factors, including mobility statistics, traffic count data, points of interest, and adjustable scenario parameters. The developed methodology allows for the estimation of charging demand at specific locations, providing valuable insights for both current infrastructure optimization and future planning. By visualizing the charging demand and unmet needs, this research equips decision-makers with a powerful tool to enhance EV charging infrastructure development and sustainability. As we strive towards a greener and more electric future, this study contributes to the essential groundwork required to support the widespread adoption of electric vehicles, facilitating cleaner and more efficient transportation systems.

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Capacity Utilisation and Estimated Profitability of Public Fast Charging Stations in Norway

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Abstract. In this paper we set out to determine the profitability of public fast charging stations in Norway based on data from actual use of the infrastructure. With estimated costs for investment and operation, we find that a significant share of the available charging stations was profitable with the current usage pattern. A sensitivity analysis showed that the pricing scheme were the most influential factor in the analysis. If we include a funding policy in the calculation, almost all stations were found to be profitable. This emphasizes the need for funding in a starting phase for charging infrastructure, or for fast charging stations in remote areas to provide sufficient charging options on long distance trips.

Keywords: Charging Infrastructure · Battery Electric Vehicles · Profitability

1 Introduction

In Norway, the transition towards a fleet of battery electric vehicles (BEV) is promising. As of 2022, 533 000 of 3 000 000 passenger cars are BEVs, and about 8 of 10 new passenger cars sold are BEVs [1]. To facilitate long distance trips, a parallel increase in fast charging infrastructure has been seen. In 2022, there were 5000 fast charging points available in Norway, and the expected number for 2030 is 10 000–15 000 [2]. Many of the first public fast charging stations in Norway were subsidized, and especially the ones in remote locations with a low expected number of visits. However, as the increase in long distance trips and following charging demand increased, the expansion of charging infrastructure was mostly market based without governmental funding schemes. With the relatively high cost of infrastructure, the charging point operators (CPO) have set a price model for charging based on their investments to be profitable. Since this is a competitive market, the CPOs business models are highly sensitive information. An open distribution of costs and income could potentially be exploited by their competitors. Therefore, it is hard to say if charging stations are profitable for the CPOs.

To ensure that the goal of a zero-emission car fleet is achieved, a continued expansion of the charging infrastructure network is necessary [3]. The projected increase of 100–200% in 2030 will require a substantial effort by CPOs, both existing and new to the market. Any knowledge about the existing market which will help this expansion should

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benefit all actors. Investment decisions should be done on the most updated information to ensure the best possible business case for the CPOs, and thereby set them in the position for additional investments in charging infrastructure. We therefore seek to provide an objective view on the profitability of existing charging stations in Norway. This is done by analyzing the usage of Norwegian fast charging stations over one year to estimate the income for the CPO, and combining this with estimated investment and operating costs.

2 Data and Methodology

2.1 About the Dataset

NOBIL is a database owned by ENOVA, a state enterprise for funding under the Ministry of Climate and Environment, and maintained by the Norwegian EV Association. It is a comprehensive database containing information about charging opportunities for BEVs. A significant share of the charging stations in NOBIL supply real-time data about occupancy of the charging points, available through an API. Data from this API has been recorded using a script which retrieves data every second and stores any changes in the availability of each registered charging point. In our study, data from a whole year (2021) is used. The data in NOBIL is stored for each individual connector in a charging station. A station is in the NOBIL database defined as a collection of charging connectors from the same operator. NOBIL also contain information about the maximum power and type (CCS or CHADeMO) for each connector. The geographical position and operator of the station are acquired from the general attributes for each station.

The live updates state whether the charging station is occupied or not. The status of the charging station together with the timestamps can be used to estimate the total charging time for each station. The data is used to calculate the annual average charging time for a station. All stations included in the analysis have been active the whole period, although some individual connectors may have been inactive. In this study, we focus on fast charging stations. Thus, only connectors with a charging capacity of more than 50 kW are included. A total of 869 connectors from 167 stations fulfilled the requirements. The connectors had charging capacities of 50 kW, 75 kW and 150 kW and none of stations had connectors with more than two different charging capacities. All stations were owned by the same CPO, Mer. For simplicity, a period of one whole year is chosen for the study. This limits the dataset to time intervals from 1.1.2021 to 1.1.2022, and only chargers active during the period were included.

2.2 Methodology

The internal rate of return (IRR) is used to calculate the profitability of a project. IRR is the interest rate required to make the net present value (NPV) of a project equal to zero for the chosen period. The projects with the highest IRR are considered the most profitable, as they give the largest return on investment. IRR is equal to the expected annual growth rate of a project. The annual cash flow for year number i is estimated using the formula:

$$CS_i = (1-t)\Big((EP - EC)(1+g)^{(i-1)} - O\Big) + dt \tag{1}$$

which is based on Eq. (2) in [4]. The range of i is 1 to 10, as the initial year 0 only has investment costs and the lifetime of the installation is estimated to be 10 years. Here, EP is the price the customer pays for the energy, EC is the electricity and grid rent costs, g is the annual expected growth in energy output, t is the tax rate, O is the estimated operational costs and d is the depreciation of the chargers. Tax is only paid when the business generates profit. For the tenth year, a salvage value is added in the calculation. To estimate the price paid by the customer in each charging session, we applied the price model used by the CPO Mer in 2021. Here, the price consisted of one component related to the transferred energy in 3 NOK/kWh and another component related to the duration in 1.5 NOK/min. The electricity price and the charging prices are constant during the period, both across time and location. The operational expenses are set to 7% of the initial charger costs [4], while cost numbers for electricity and installation of charging stations are based on a study by DNV GL [5]. Costs for land and other costs with local variation are excluded since they vary greatly from place to place, although it is included to some degree in the other investment costs which are set to 55% of the cost of the chargers. The cost of connecting to the grid is also included here, but this is largely dependent on location and the capacity needed.

Accepting a project with an IRR of 6% is equivalent to accepting a project with a positive NPV calculated with a discount rate of 6%. IRR is a relative measure of the return, while the NPV returns absolute values. If one were to evaluate the return of the project regardless of the capital expenses, using the IRR would be preferable. However, the IRR does not always exist. NPV, on the other hand, will always return a value and is therefore the main metric in this analysis. Here, a station is considered profitable if it has an IRR of at least 6%, i.e. the NPV is at least zero.

3 Analysis

For each of the charging stations included in the analysis, a time series of charging sessions was the starting point of the analysis. For simplicity, it was assumed that all connectors of all charging stations supply energy with equal and constant efficiency. The efficiency is the ratio between the average power delivered to the vehicle and the charging capacity of the connector. The duration of the charging session multiplied with the charging capacity and the efficiency equals the energy the vehicle is assumed to receive, and that the customer pays for. The energy delivered from each station calculated from the dataset is set as a base for year one and is expected to increase with a certain percentage per year.

For the main scenario, the cash flow was calculated yearly for each station from year 0 to year 10 based on Eq. (1). We also added a scenario which included state funding from ENOVA. Enova funding has been given in several rounds with different values and requirements. In this analysis, the funding policy from 2016 is used, because such funding has knowingly been given for some of the stations in the dataset [6]. The funding covers charging costs up to 300 000 NOK per charger, in addition to all other capital expenses. As a simplification, the funding is applied to all stations in the sensitivity analysis to assess the effect on the profitability. The amount of the funding is not adjusted for inflation, as the price of technology often goes down as it becomes more established. For the funding scenario, depreciations equivalent to the amount of support for the charger costs will not take place. The depreciations are therefore removed from the NPV in this scenario, but without taking into account the discount rate, i.e. the time value of money.

4 Results

The result from the analysis is shown in Fig. 1 for both the main and the funding scenario. In the main scenario, we see that the charging stations which are profitable (green) are in general in urban areas, while the unprofitable (red) are in remote areas. When including funding, a large share of the unprofitable charging stations become profitable. For the base case, 71% of the stations were considered profitable. The stations had an average net present value of 1,2 million NOK. When the funding policy described in the assumptions is applied, the share of profitable stations increases to 98% and the average NPV more than doubles.

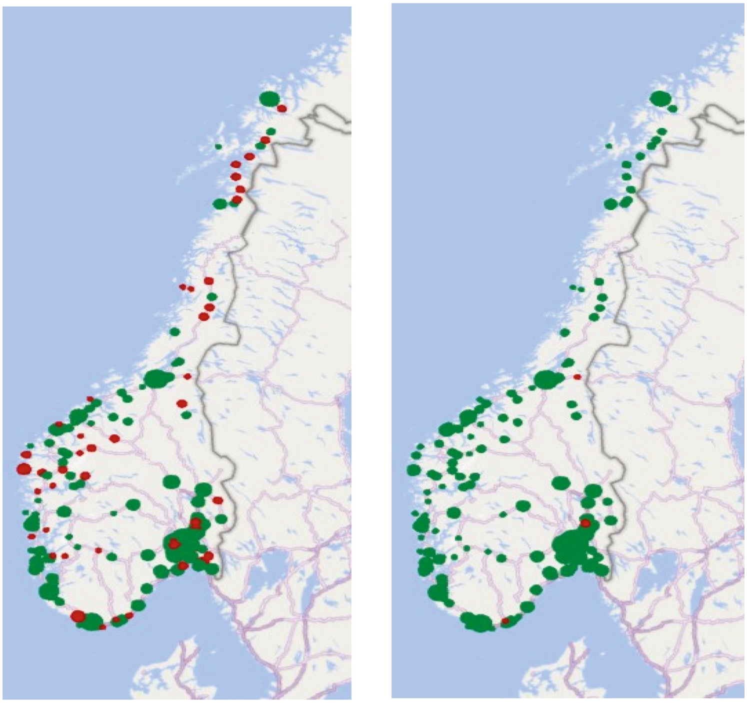

Fig. 1. Left: Base case. Green dots are profitable stations, red are non-profitable. The size is proportional to the number of fast chargers at the station. Right: Funding scenario. Green dots are profitable stations, red are non-profitable. (Image produced using Bing Maps.)

The impact of change in each variable is assessed by finding the share of profitable stations for a 20% decrease and increase in the variable, as shown in Fig. 2. The share of profitable stations is the number of stations that are considered profitable divided by the total number of stations, which in this case is 167. The sensitivities are given in percent change in the variables, i.e. for an efficiency at 80%, the –20%/20% values are 0,64 and 0,96.

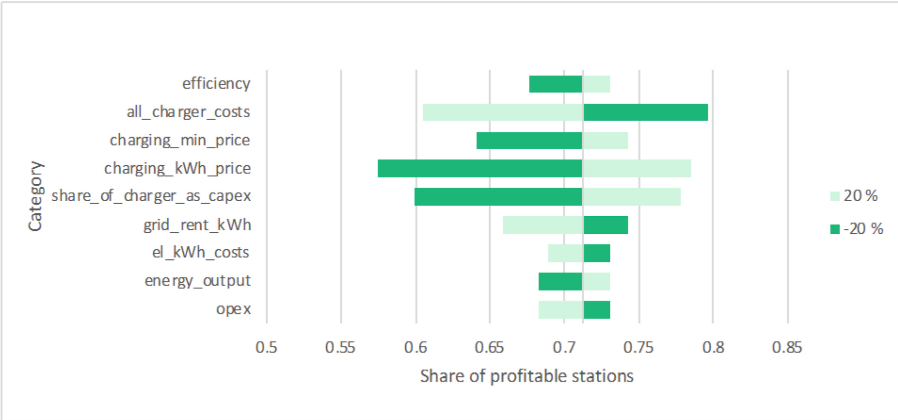

Fig. 2. Change in the share of profitable stations based on change in values for the different parameters.

5 Discussion

Although the presented results are based on a large number of observed charging sessions, there are several assumptions in the methodology which leads to uncertainty in the results. The data from NOBIL only shows whether a vehicle is connected to the connector, not if it is actually charging. In addition, the estimated energy transfer adds to the uncertainty.

Some stations have connectors with charging capacities less than 50 kW, and that is likely also the case for some chargers. Because the analysis is focusing on fast charging stations, these connectors are not included in the analysis. This may cause the profitability of a charging station to appear lower than it is, because a connector with a lower capacity that belongs to the same charger as a fast-charging connector will cause extra income, but likely little extra costs, since the capacity is already included.

The annual energy output of the station is assumed to be constant during the analysis period. The actual energy output of fast chargers is expected to increase as a result of the increase of electric vehicles. The result of this depends, however, on the ratio of chargers to vehicles.

6 Concluding Remarks and Suggestions for Future Work

The results from the study indicate that large stations in urban areas are generally more profitable. According to the sensitivity analysis, changes in charger costs and other capital expenses (indicated by the share of chargers of the total capex) and charging price per kWh seem to be the most determining factors in whether a station is profitable. The capital expenses make up the highest costs. The charging price is the only income. What matters is not the charging price or electricity costs, but the difference between them. The charging price per kWh has the highest sensitivity because it has the highest value. Funding leads to a high increase in the share of profitable stations since it eliminates most of the capital expenses. Not considering the time value of money when removing the depreciations leads to a more conservative estimate in terms of the average NPV, but the impact is small. The number profitable stations remain the same as if funding was applied and the depreciations were not removed.

There are some aspects in this study which could be improved in further research. It may fail to assess the profitability of individual stations because of the generalized parameter values. Possible future work may consider geographical and spatial variations, especially for the costs. In addition, the effect of inflation could be included. A further investigation of costs could render the model being useful for estimating optimal placement of charging infrastructure to get the highest energy output.

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Methodology for Continuous Planning of Charging Infrastructure in the Face of Uncertainty and Change

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Abstract. Charging infrastructure is the backbone of electromobility. Due to new charging behaviors and power distribution constraints, the energy demand and supply patterns of electromobility and the locations of current refueling stations are misaligned. Infrastructure developers (charging point operators, fleet operators, grid operators, and real-estate developers) need new methodologies and tools that help reduce the cost and risk of investments so that they can quickly roll out infrastructure that enables large-scale EV adoption in all segments and accelerates the green transition of the transport sector. To this extent we propose a transport energy demand centric dynamic adaptive planning approach and a data-driven Spatial Decision Support System (SDSS). In it, with the help of a realistic digital twin of an electrified road transport system, infrastructure developers can quickly and accurately estimate key performance measures (e.g., charging demand, BEV enablement) of a candidate charging location or a network of locations under user-specified transport electrification scenarios and interactively and continuously adjust and reoptimize network plans as facts about the deep uncertainties about the supply side of transport electrification (i.e., access the grid capacity and real-estate and presence of competition) are gradually discovered/observed. The paper describes components and functional support of the system that is available as of a web based platform to support the planning of public fast charging networks for freight and long-distance private car trips in 26 European countries (https://thegordian.io/) and has been used in commercial pilots in both competitive and collaborative settings.

Keywords: Charging Infrastructure Planning · Deep Uncertainties · Dynamic Adaptive Planning · Route Based Network Effects

1 Introduction

The importance of a timely rollout of charging infrastructure that meets the spatial energy demand pattern of electromobility with matching charging supply capacity cannot be understated. It drives EV adoption and the green transition of the transport sector. A

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charging supply pattern that closely matches the charging demand is also the foundation of transport operations on the infrastructure and the closeness of the match will ultimately determine limits of charging infrastructure utilization and transport costs in an electrified road transport system.

The infrastructure design challenge is manyfold. First, the currently dominating home-, depot-, terminal-, and destination charging behaviors shaped by the current but potentially quickly or abruptly changing technical capabilities (e.g., MCS, new battery technologies representing longer vehicle ranges and shorter charging times, dynamic charging, battery swapping, etc.) represent a major transport energy demand shift in space and time. Second, on the energy supply side, the access to-, the cost of-, and the development lead times of grid transmission capacity are limited at locations and times, are not known globally, and can be excessive, respectively. Furthermore the grid capacity aspects are clearly network dependent. Third, the locations of current refueling infrastructures have evolved over a century to cater for the energy demands of a fossil fuel- and internal combustion engine based road transport system and are not aligned in space and service offerings with the energy and charging demand patterns of electromobility. In relation, the access to-, the cost, and the development lead times of the suitable new real-estate and services is also limited and can be excessive. Fourth, in addition to purchase and operations costs, vehicle adoption rates and spatial patterns are a large extent influenced by the accessibility and convenience of charging services. Finally, while policies, regulations and subsidies can steer and to some extent coordinate infrastructure developments, charging infrastructure is primarily developed opportunistically and in competition by multiple economic actors of different types that have different and often conflicting business objectives. The above described connected and moving parts are collectively referred to as *deep uncertainties of transport electrification.* There is a large body of scientific evidence that human reasoning and intuition cannot manage these uncertainties as they often fail to account for feedback loops, non-linearity [4], and the important transport route based network dependencies in electromobility (see Sect. 2.2). This failure leads to suboptimal and inefficient developments, a fear of lost assets, hesitant investments, and ultimately a slow transition.

The key role of charging infrastructure is widely recognized, and many researchers have developed methodologies and case studies to deliver decision support. For detailed literature reviews and summaries from different perspectives see [1, 7–9]. One can classify methods in terms of their 1) primary design data source (road network, vehicle counts/traffic flows, origin-destination flows, transport routes, GPS logs), 2) charging network design/optimization objectives (even network coverage, demand coverage that maximizes the flows passing through with or without double counting and taking into account multiple stops due to range limitations [1, 8, 9], utilizing logistics patterns (e.g., frequency and duration of stops) [7] and drive-time and rest-stop regulation [8]), and system boundaries/focus for infrastructure planning (charging infrastructure network planning in the transport network, power distribution network planning, and integrated planning) [10]. In relation, the herein proposed methodology primarily uses transport routes to design and optimize for demand coverage that maximizes the flows passing through without double counting and considering multiple stops due to range limitations. The proposed methodology is in sharp contrast to the single objective-, single economic actor focused-, and static decision support that any previous work provides as follows. First, it supports an analyst to evaluate and optimize charging plans under different transport electrification scenarios from/with multiple user-defined perspectives/objectives. Second, it implements a generic, interactive and incremental charging network planning process that support in infrastructure developers in multiple types of analysis (network location validation and ranking, network expansion, etc.). Third, it supports the dynamic adaptive planning paradigm [5] to manage the deep uncertainties related to access and cost of grid capacity and real estate and the impacts of competition from multiple independent actors. Finally, the methodology can be applied in collaborative planning practices to support the efficient allocation of charging infrastructure subsidies.

2 Methodology

2.1 Design Principles

The methodology is rooted in three design principles. First, planning is a continuous process during which plans have to be revised as new information becomes available. Second, plans, especially network plans, are holistic, i.e., the parts of the plans depend on each other and when a part is changed, potentially all parts of the plan have to be reevaluated and potentially revised (see Sect. 2.2). Finally, while data, analytics, visualizations, models and simulations can aid an analyst in making rational decisions by enforcing that the decisions fulfill multiple criteria or maximize one or more objectives, for a number of reasons any successful computerized decision support system has to allow its user to freely alter a plan regardless of its criteria fulfillment or optimality.

2.2 Theoretical Foundations for Demand Centric Charging Network Design

For the purposes of long-term charging infrastructure planning, the geometries and weights of transports along routes on a road network can accurately capture most important aspect of transport electrification [2]. These include the energy-use of vehicles, their arrival State of Charge (SoC) and hence charging demand at stations in a network, as well as which transport routes a network of stations enable the full electric operations of. In particular, as Fig. 1 illustrates, under a logical energy-use and charging behavior model (described in Sect. 2.4), the charging demand (e.g., number of charging sessions) has only a weak relation to the traffic flows or vehicle counts. Furthermore, the charging demands at stations in a network affect each other. On one hand, two nearby stations can serve the charging need of a specific transport route and thereby loose charging demand to each other. On the other hand, as the network is expanded with a station (see Plan B in Fig. 1.), the expansion can enable the electric operations of new transport routes and thereby generate charging demand on other stations. The losses tend to be more local but are not merely based on the road network distance between stations but rather on the transport work along the transport routes that link the stations. In comparison, a network expansion can induce charging demand at any station in the network.

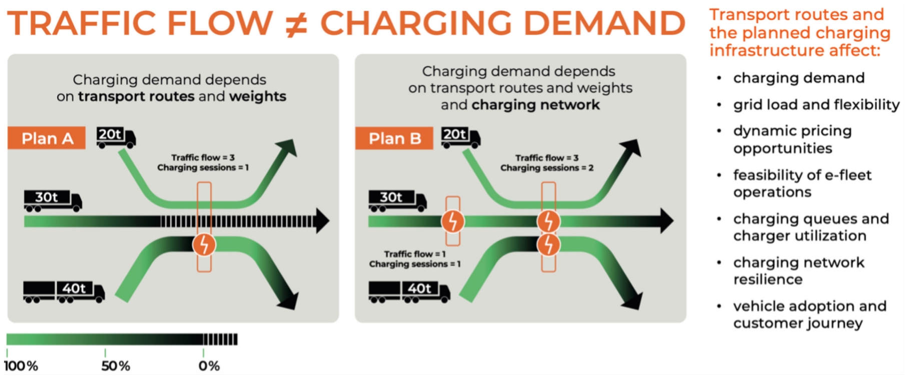

Fig. 1. Importance of route based network effects in demand centric transport electrification and the lack of information in traffic flows. Source [2].

2.3 Data

As several aspects have to be considered during planning, the designed SDSS contains a collection of geographical data layers that are harmonized and kept up-to-date for easy decision making. The layers include the existing charging stations, the truck stops with their services, the patterns of commercial logistics in the form of the prevalence of short and long truck stoppings from the European Automobile Manufacturers' Association (ACEA) analysis [4], (where available) the high/medium voltage grid transmission/distribution lines, the locations of regional transformers, the terrain and land cover-based cost estimate for 10 MW grid connection to nearest regional transformer, (where available) the restriction and priority areas for subsidies, and most importantly 100s of millions of synthetic annual freight- and long-distance private car trips across 26 countries in Europe based on the ETIS Plus project [3].

2.4 Transport Electrification Scenario Assumptions

Any analysis in the SDSS is for a user-defined transport electrification scenario that consists of an electric vehicle-, an energy-use/consumption- and a charging (behavior) model. Optionally, the scenario can include an initial network of existing or planned stations of the customer and/or competitors (see Sect. 2.7). The analyst can make assumptions about these components of the scenario and set its *parameters*.

The vehicle model is specified by a *battery size* and *energy-use*: the amount of energy that a vehicle propulsion system needs to move a unit of transport weight over a unit distance. For long-term charging infrastructure planning purposes for typical electric heavy-duty vehicles (HDVs) (e.g. Scania or Volvo) and heavy freight transports, the average energy-use is approximately 0.035 kWh/tkm.

The charging (behavior) model assumes a certain level of *initial SoC* primarily from depot charging but potentially also from prior transport trips. The charging amount at stations is limited by the *battery size*, the arrival SoC, the *maximum rest-stop duration*, the *charging power*, and the energy that is needed to operate the route. The model allows two *charging options*: vehicles either stop to *charge at all stations* along their routes or *only when their SoC is below a threshold*.

2.5 Charging Network Demand Concepts

A number of route based network demand concepts and analytics are at the heart of the SDSS. The more central concepts and analytics include: route catchment, demand in isolation, demand in network, demand from fully electric, total network demand, losses due to canibalization and competition, losses inflicted via canibalization and on competition, CO2 displacement from charging at a given location, increase in number of fully electric routes by adding a given location to the network, and increase in ton-kilometers (tkm) of fully electrified routes by adding a given location to the network. These are in detail described in [4].

2.6 Multi Criteria Evaluation Framework

The SDSS adapts a Multi Criteria Evaluation (MCE) that is an intuitive, effective and widely used method in Geographic Information Systems (GIS) to evaluate the suitability of locations from multiple perspective [6]. The SDSS according to the MCE methodology calculates spatial proximity based factors from the geographical layers (Sect. 2.3) as well as analytics factors for the charging network demand concepts (Sect. 2.5) and calculates a single score for a location as a weighted average of the scores based on the analyst's preferences. The scores can be used to compare, rank, and determine infrastructure rollout plans.

2.7 Interactive Planning Process for Multiple Scenario Analysis Types

Using the above data, scenario assumptions/models, concepts, and framework (Sects. 2.2–2.6), the SDSS supports multiple scenario analysis types with a simple interactive and iterative planning process that is shown in Fig. 2.

2.8 Analysis Reports

While the SDSS supports the management of multiple plans for multiple scenarios that the analyst can explore and continuously develop according to the dynamic adaptive planning paradigm, it can also produce a "*Station ranking and transport electrification impact report*"[1], which provides a summary of a plan for a transport electrification scenario, and individual "*Station performance reports*"[2]. See links in footnote for samples.

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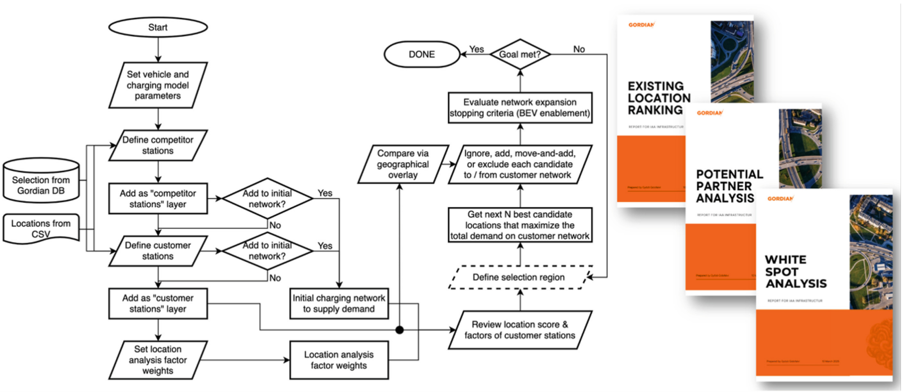

Fig. 2. Planning process and analysis types supported by the SDSS.

3 Past and Future Usage of the SDSS

The SDSS has been commercially used to plan the initial HDV charging network of a large charging point operator in Scandinavia and in a collaborative setting to evaluate the transport electrification impact of strategic charging network subsidies. In the future we aim to make the SDSS available via the Alternative Fuels Infrastructure Regulation (AFIR) Observatory and extend it with network resilience- and spatial sensitivity analysis functionality.

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An Online Tool for Guiding Bus Fleet Decarbonisation Through Green Hydrogen and Electrification

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Abstract. The transition to zero emission bus (ZEB) fleets is accelerating. Two prevalent ZEB options that are often compared to each other are battery electric buses (BEBs) and fuel cell electric buses (FCEBs) fueled by green hydrogen. Hydrogen is labelled as green when it is produced by electrolysis powered by renewable electricity. From the perspective of a bus fleet operator or regional authority interested in replacing a conventional diesel bus fleet with one of these new technologies, it can be unclear which combinations of BEBs and FCEBs are most suitable in terms of cost, emission reduction, and capability to maintain regular operation of the bus fleet. This work develops the Enabling Support Tool (EST), an easy-to-use model that can assess the trade-offs between BEBs and FCEBs in terms of their technical performance, required infrastructure, cost, and emissions reduction potential. Using a novel input process that does not require complex drive-cycle data, the EST allows the user to quickly investigate the feasibility of a mixed fleet of BEBs and FCEBs, considering the effects of local climate conditions, road gradient, and varying bus payload on the daily range of BEBs. This enables users to explore the feasibility of different combinations of BEBs and FCEBs and thus guide cost-effective full fleet decarbonisation.

Keywords: Decarbonisation · Bus Fleet · Green Hydrogen

1 Introduction

There is currently a wide range of ZEB types on the market, each with their own advantages and disadvantages, therefore bus fleet operators and regional authorities must choose carefully when transitioning to a ZEB fleet. While battery electric buses (BEBs) are usually the cheapest zero-emission choice due to their relative technological maturity, they suffer from range and autonomy limitations due to the relatively poor energy density of batteries and their relatively long recharging times. This means that in some cases, fleet operators must increase the battery size, add extra buses, or invest in opportunity charging infrastructure that can recharge buses during operation, which leads to additional costs. In this case, it could be more economically feasible to invest in a ZEB

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with higher range and autonomy, for example a fuel cell electric bus (FCEB) fuelled by hydrogen. If this hydrogen is produced by electrolysis powered by renewable electricity, the term "green hydrogen" is used. FCEBs have a range comparable to conventional diesel-powered internal combustion engine buses (ICEBs) and can be fully refuelled in 10 to 15 min [1], making them an attractive option for when BEBs do not have sufficient range.

While FCEBs usually have a greater range and autonomy than BEBs, they are currently more expensive due to lacks of existing green hydrogen supply, hydrogen dispensing infrastructure, and economies of scale for key components such as fuel cells and compressors [2]. Studies have shown that, while BEBs are cheaper than FCEBs for shorter, less energy-intensive routes, FCEBs can become cost competitive when operated on longer, more energy-intensive routes [3]. In addition to route length, other significant parameters affecting the energy consumption of buses are the road gradient, the mass of the bus, and the energy demand of onboard auxiliary equipment, especially heating ventilation and air conditioning (HVAC) systems.

From the perspective of a bus fleet operator or transport authority trying to decide between BEBs, FCEBs, or a combination of the two, it may not be obvious which option they should choose, as the operational performance and economic feasibility of these buses is largely dependent on the parameters presented above. Finding a solution can therefore be a complex and time-consuming task. Thus, the goal of this work is to aid a successful transition to climate neutrality in city bus fleets by developing the Enabling Support Tool (EST), a model that can be transferred to an online platform and used by bus fleet operators, regional authorities, and other relevant stakeholders to quickly analyse and compare the suitability of ZEB technologies for existing bus fleets.

2 Methodology

2.1 Main Outputs and Equations

The most common metric used by fleet operators to quantify and predict the cost of a bus fleet over its lifetime is total cost of ownership (TCO). This metric is useful as it includes the discounted sum of all cashflows over the lifetime of the bus fleet, and it can be expressed in units of €/km. For bus fleets, the TCO consists of operational expenditures such as fuel, maintenance and driver wages, and capital expenditures such as buses, charging/refuelling infrastructure and batteries. Driver wages are a function of operational hours and hence they are the same regardless of bus powertrain type. The EST is intended for the comparative assessment of bus fleets with different powertrain types, and so driver wages are excluded from the TCO calculation.

Four fleet configurations can be compared using the EST; a fleet of ICEBs, a fleet of overnight-charged BEBs, a fleet of FCEBs, and a mixed fleet consisting of overnight charged BEBs and FCEBs. The proportion of BEBs to FCEBs in the mixed fleet is calculated by the EST based on the method described in Sect. 2.2. The EST allows users to input three different bus sizes. The three most common city bus sizes are considered: (1) 12 m single-deck (SD), (2) 12 m double-deck (DD) and (3) 18 m Articulated (AR). In this paper, the term city bus refers to a bus that serves either intra-city routes (referred to as urban) or routes that connect cities with nearby regions (referred to as regional). The TCO for the four fleet configurations is calculated using Eq. (1) below.

$$TCO = \frac{C_F + C_M + C_I + C_{bus} + C_{bat}}{D} \tag{1}$$

where C_F is the fuel cost, C_M is the maintenance cost, C_I is the infrastructure cost, C_{bus} is the bus acquisition cost, C_{bat} is the battery cost, and D is the total distance travelled by all buses in the fleet over its economic lifetime.

While TCO is a useful indicator of the economic cost of a bus fleet, it does not give insight into the environmental cost of the fleet. For this purpose, the total cost of abatement (TCA) can be used. TCA is a metric for the cost of abating or avoiding one tonne of CO_2 emissions by transitioning from a conventional fleet to a ZEB fleet. This can provide insight into how expensive it will be to move from a conventional ICEB fleet to a ZEB fleet. TCA (with units of €/t_{CO2}) can be calculated using Eq. (2) below. The TCO of the ZEB bus fleet (TCO_{ZEB}) and ICEB bus fleet (TCO_{ICEB}) are calculated as described in Eq. 1.

$$TCA = \frac{(TCO_{ZEB} - TCO_{ICEB}) \times D}{M_{WTW,ICEB_n} - M_{WTW,ZEB_n}} \tag{2}$$

$M_{WTW,ICEB_n}$ and M_{WTW,ZEB_n} represent the total well-to-wheel (WTW) emissions (t_{CO2}/year) of the ICEB and ZEB fleet respectively in year n. WTW emissions include the CO_2 emissions released during the production and transportation of the fuel/energy used by the buses (well-to-tank) and the CO_2 emissions released by the buses themselves during operation (tank-to-wheel).

2.2 Fleet Replacement Rules and Model Inputs

To meet the operational requirements of the user's existing ICEB fleet, there are two key conditions that must be met by every bus in the ZEB fleet:

1. **Size** – the bus must carry the same number of passengers as the bus it is replacing.
2. **Range** – the bus must be able to drive the same number of kilometres per day as the bus it is replacing. The term used in this study for the distance driven by a bus in a day of operation is utilisation rate given in units of km/day/bus.

With a tank capacity of up to 40 kgH2 [4] and an average SFC of 7 kg/100 km [1], FCEBs can have a maximum range of 570 km. As the SFC is improving with each new generation of FCEBs [5], this maximum range is expected to increase further over the coming years. While this means that FCEBs have a comparable range to ICEBs, there is still a range disparity as ICEBs can achieve a maximum range of up to 900–1,100 km on a full tank, assuming a large tank capacity of 450 L and an SFC of 40–50 L/100 km. Based on interviews and timetable data collected from bus operators in Ireland, Saarland, Luxembourg and the Netherlands, it was found that the vast majority of city buses have utilisation rates between 50–500 km/day. In this work it is therefore assumed that the utilisation rates of city buses rarely exceed the range of FCEBs. In the rare case that the utilisation rate does exceed the range of an FCEB, it is unlikely that an extra bus would be required. This is because FCEBs can be quickly topped up with fuel during the day and put back into service with minimal impact on their availability, in a similar manner to ICEBs [1]. Therefore, for the FCEB fleet, it is assumed that all buses can match the range of ICEBs, and no extra buses are required. For the BEB fleet, the range of the bus is a function of its battery size. Therefore, the model sizes the batteries so that the buses can meet the utilisation rates that the user inputs – the battery sizing methodology is omitted due to word count limitations. Due to EU gross vehicle weight (GVW) restrictions for buses [6], each bus size has a maximum possible weight, and therefore a maximum possible battery size. If the maximum battery size is reached, an extra bus is added to maintain fleet operations. It is then assumed that these two buses drive half the distance and have half the operational hours of the original bus. Their batteries are then resized to correspond to the lower daily energy demand required of them.

The basic rule of the mixed fleet is that FCEBs are used to replace buses with a utilisation rate exceeding the maximum range of a BEB, and BEBs are used to replace buses with a utilisation rate below the maximum range of a BEB. This ensures that all buses in the new fleet can meet the range requirements of the existing fleet.

3 Results and Discussion

Figure 1 shows the calculated TCO of a fleet of ICEBs, BEBs, FCEBs, and a mixed fleet of 15 FCEBs and 16 BEBs in Galway city. The ICEB fleet is the cheapest with a TCO of 1.05 €/km due to the lack of infrastructure costs and cheaper bus cost. Hence, the ICEB fleet TCO is mainly composed of the operational expenditure related to buying the diesel. The TCO of the BEB fleet is dominated by the capital expenditure of the buses and the batteries, with the requirement of 15 extra buses increasing the TCO by 0.21 €/km. At the high hydrogen price, the FCEB fleet and mixed fleet are the most expensive due to the high cost of fuel, buses and hydrogen refuelling infrastructure. However, reducing the cost of hydrogen has a significant impact on their TCO, particularly for the FCEB fleet, where a cost of hydrogen of 2 €/kg brings the TCO in line with the ICEB fleet. This highlights the importance of subsidies for green hydrogen, as a subsidy of a few euros per kg can significantly decrease the TCO and make FCEB fleets more appealing to fleet operators. An example of such a subsidy can be seen in the United States, where a subsidy of 3 $/kg can be granted to projects with a lifecycle greenhouse gas emissions intensity of less than 0.45 $kgCO_2e/kgH_2$ under the Inflation Reduction Act.

The mixed fleet is not as susceptible to changes in the price of hydrogen and it does not reach cost parity with the ICEB fleet even at a very low hydrogen price. However, the mixed fleet does become cheaper than the BEB fleet at a hydrogen price of 10.30 €/kg. The FCEB fleet becomes cheaper than the BEB fleet at a hydrogen price of 7.70 €/kg.

Figure 2 presents the TCA of the three ZEB fleets. The cost of abating one tonne of CO2 by moving to a BEB fleet is €235. For comparison, the carbon tax in Ireland at the time of writing is 48.50 €/t_{CO2}. At a median hydrogen price of 7 €/kg, the TCA of the FCEB and mixed fleet is 189 €/t_{CO2} and 149 €/t_{CO2} respectively. At the lower hydrogen price of 2 €/kg, the TCA drops significantly to 3 €/t_{CO2} and 33 €/t_{CO2} respectively.

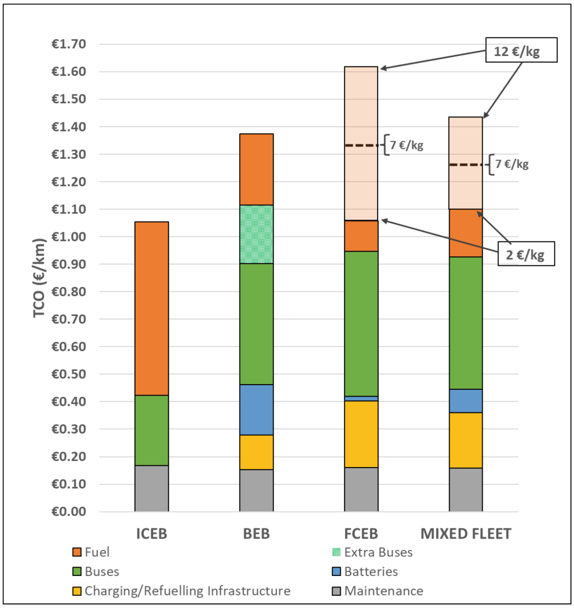

Fig. 1. Bus fleet TCO breakdown for Galway city

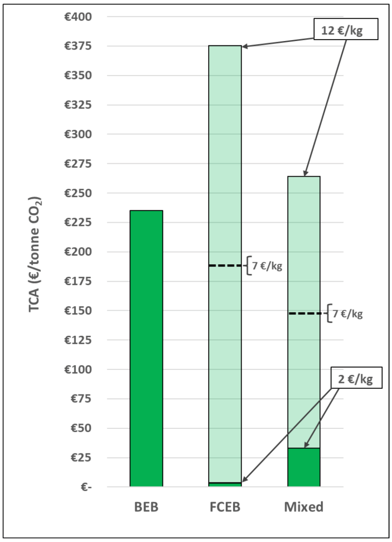

Fig. 2. Bus fleet TCA for Galway city

4 Conclusions

This paper presents a novel SFC-based bus fleet cost and emissions model that can be used as a tool to aid decision-making in the transition to ZEB fleets. The model considers the effect of local climate conditions, road gradient, and varying bus payload on the energy consumption of BEBs and FCEBs to allow for the comparison and optimal combination of the two technologies in different regions. By employing a novel input process requiring minimal data pre-preparation and inputs, the model remains easy to use while offering instructive insight.

A case study of the Galway city bus fleet was performed to demonstrate the model. Results showed that green hydrogen is particularly beneficial for double-deck buses due to the limited range of double-deck BEBs, leading to a mixed fleet of BEBs and FCEBs being the most economically attractive ZEB option.

As part of the EU Interreg North-West Europe funded GenComm project, a simplified version of the model described in this paper was implemented as a free online tool called the Enabling Support Tool, available on the Community Hydrogen Forum: https://communityh2.eu/ [7].

Given the current climate crisis and need for rapid decarbonisation in the public transport sector, it is essential that the optimal route to zero carbon bus fleets can be identified quickly. The model proposed in this paper can enable a faster transition to zero carbon by serving as an interactive scoping tool that can be used to analyse entire bus fleets quickly and give users an initial estimation of the techno-economic feasibility of BEBs and FCEBs for their fleet. The model also features easily adjustable technical and economic parameters that can allow users to create case studies and scenarios to help inform evidence-based policy decisions around green hydrogen and electrification in public transport.

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Project EcoFuel: Renewable Electricity-Based, Cyclic and Economic Production of Fuel

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Abstract. E-fuels, produced from CO_2 using renewable electricity, currently suffer from low energy efficiency, hence high energy demand, related high cost and are therefore not yet produced at industrial scale. To be commercially viable, e-fuels production pathways require the availability of vast amounts of low-cost electricity. The Horizon 2020 project EcoFuel, with the aim of overcoming these deficiencies, develops and demonstrates a novel process chain that significantly improves the energy efficiency for production of synthetic fuel out of CO_2 and water using renewable energy. The process chain comprises a) the supply of CO_2 from the atmosphere via a novel direct air capture (DAC) approach, b) direct electro-catalytic reduction of CO_2 to C2/C3 hydrocarbons at close to ambient temperatures, and c) thermo-catalytic liquefaction of alkenes, upgrading and fractionation into transport fuels. The direct electro-catalytic CO_2 reduction to hydrocarbons offers greatly enhanced efficiency potentials compared to Power-to-X technologies downstream of water electrolysis and at the same time, reduces process pathway steps. Overarching objectives of EcoFuel are to reduce primary energy demand, to enhance resource and cost efficiency of production, minimize the environmental footprint of the process, and to demonstrate the ecological and economic advantage.

Keywords: e-fuel · synthetic fuel · DAC direct air capture · CCUS · LCA · TEA

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1 Introduction

Carbon Capture and following electrochemical conversion of CO_2 into fuels has immense potential to defossilize industry sectors and provide an alternative storage solution for intermittent renewable energy supply. Such sustainable fuels are one of the important pillars for reaching 'net zero' emissions by 2050, especially in hard-to-abate applications of the transport sector like aviation, maritime or the heavy-duty long-haul trucking. The Renewable Energy Directive and its updates [1] set target quotas for energy carriers of non-biological origin.

Today's drawbacks of synthetic fuels are the energy demand for the production, the related energy cost, and their large-scale availability. EcoFuel tackles the challenges of energy demand, envisaging an upscaling to industrialization.

2 The EcoFuel Project and Process Steps

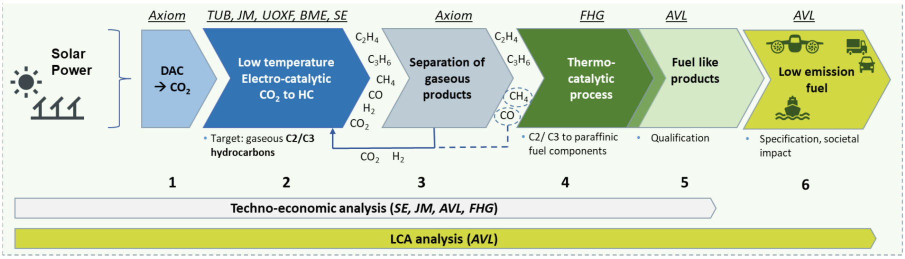

Fig. 1. Overview EcoFuel process. Image courtesy of EcoFuel project, reproduced with permission

EcoFuel develops and demonstrates a novel process chain (Fig. 1) that significantly improves the energy efficiency for production of synthetic fuel out of CO_2 and water. The implementation of this new process chain has the potential to boost the electricity-to-liquid hydrocarbon fuel molecule efficiency to a final value of 54% in optimized industrialization, thus saving huge amounts of valuable renewable energy for the future mass production of CO_2 neutral, sustainable fuels. The first half of the project was dedicated to basic research and experimental investigations of the components of the process chain. The second project half concentrated on optimization and stability of the process parameters and its elements, the set-up of an integrated 1kW electro-chemical system, and the demonstration of the combined reaction cascade. The resulting fuel precursors are qualified and assessed, the entire process chain is economically and ecologically evaluated.

Inputs for Fuel Synthesis: As means of the carbon source, the EcoFuel process employs a recently developed concept for atmospheric CO_2 capture (Fig. 2). It consists of three main steps: (i) carbon dioxide absorption on metal ion carbonates from the atmosphere, (ii) carbonate enrichment by means of electrodialysis and (iii) thermal desorption of concentrated carbon dioxide to be used as the carbon feedstock for the fuel synthesis. The three steps are interconnected by two separate liquid carbonate loops.

To demonstrate the viability of the process, all three units were designed, assembled and commissioned experimentally on a small scale and put together into operation. The carbon capture experiments proved their capability of capturing atmospheric CO_2 and providing it at high concentration and purity. In the first experiment ~ 2kg of atmospheric CO_2 were captured. The unit demonstrated that the new DAC process is capable of providing pure CO_2 process streams at a significantly reduced requirement of thermal <800 kWh (~75°C) and electrical <1500 kWh energy per ton of captured CO_2 from air, and at ≤150 €/t CO_2 cost of supply, fulfilling the set project objective. The DAC is performed with atmospheric air having ~400 ppm CO_2.

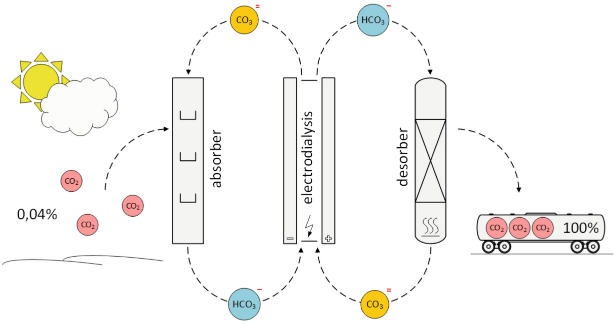

Fig. 2. Basic concept of EcoFuel DAC using ED. Image courtesy of Axiom, reproduced with permission

In addition, as feedstock for the EcoFuel process in the electro-catalytic reduction of CO_2 to C2/C3 alkenes, water is needed. Furthermore, water is required as well as process water for cooling in the thermo-catalytic process and in the DAC process as make-up of the water evaporation within the CO_2 -absorption step. In order to consider the topic of access to water in a broader context, the desalination of seawater was identified as a method with the highest potential for solving the water provision problem for the process in a study conducted. While the cost of CO_2 has a significant effect on the overall cost of synthetic fuels, the cost of water provision is less than 1% of costs for CO_2 supply.

Electrochemical CO_2 Conversion: The electro-catalytic CO_2 reduction unit (ECO2R) reduces CO_2 from the DAC to ethylene with the help of electrical energy. Intensive development work was performed on the catalysts, the electrolysis cell, cathode, anode, and related process parameters (e.g. current density).

The catalyst development focused on the synthesis and screening of new electrocatalysts for the cathodic electro-catalytic CO_2 reduction (ECO2R) and the anodic electro-catalytic oxidation of water to oxygen (OER). On the synthesis of CO2RR (CO_2 reduction reaction) catalysts, the partners focused on making Cu-based catalysts with the aim to control and improve the faradaic efficiency of C2+ gaseous hydrocarbons, while reducing that of competing products at low kinetic overpotentials. A variety of PGM and non-PGM OER catalysts were synthetized. Research on the anode catalyst was geared towards reducing and replacing noble metal catalyst components, while maintaining or lowering the kinetic overpotentials, thereby raising the energy efficiency. Durability was assessed by comparing activity loss.

For the cathode, different ionomer and GDL (gas diffusion layer) properties were also explored with the goal to prevent or delay electrode flooding in the flow cell. The CuO cathodes were tested in flow-type electrolysis cell using 200 mA/cm2 current density, in the electrocatalytically reduction of CO_2. The targeted product was ethylene.

An electrochemical cell was developed that makes use of a combination of PTFE substrates and a CuO catalyst layer for fabrication of cathode gas diffusion electrodes that allow selective CO_2 reduction to ethylene at large current densities. A scheme in Fig. 3a is provided to show the cathode GDE (gas diffusion electrode) components. In addition to our PTFE based GDE, a novel current collector was developed that enables a scale-up to 300 cm^2. Figure 3b shows one scaled up cell design that includes all necessary cell components and Fig. 3c the scaled cell stack.

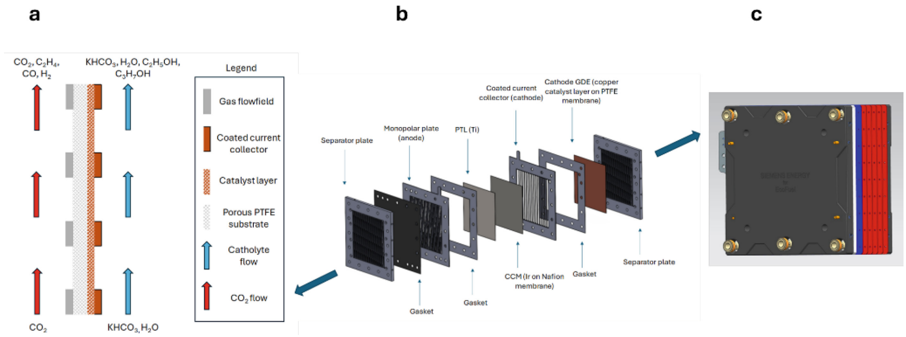

Fig. 3. Cell design for the EcoFuel electrolysis unit. **a** Schematic of the cathode. **b** Scaled-up cell including the novel current collector approach. **c** Cell stack. Image courtesy of TU Berlin, reproduced with permission

Olefin Separation Unit (OSU): The gaseous C2+ hydrocarbon feed exiting the ECO2R electrolyser cell stack is the input gas feed of the subsequent gas separation process step. An energy-efficient separation of the relevant C2+ hydrocarbons from hydrogen and unreacted CO_2, that are both fed back into the electrolyser stack to increase the electro-catalytic CO_2 conversion and energy efficiency, is necessary. This olefin separation unit (OSU) deals with the separation and enrichment of ethylene out of the effluent stream from the electro-catalytic CO_2 reduction. In a first step it separates C_2H_4 and CO from H2 and CO_2, in a second step it enriches C_2H_4 by separating CO. Using a third step, H2 is successfully separated from CO_2.

The gas feed for OTL synthesis exiting the gas separation unit will contain low levels of H2, CH_4 and CO. The developed OSU design involves a multi-permeator multi-compressor system to enrich C2+ achieving both high purity and high recovery.

Olefin to Liquid (OtL) Reaction: After the enrichment and the purification of the ethylene flow, it is sent to the chemical conversion reactor. In this fixed bed reactor, a Ni exchanged silica–aluminate material catalyses the oligomerization reaction at temperatures of 260°C and 30 bar total pressure. The targeted products are liquid fuel precursors, mainly linear and branched olefins with a carbon chain length of C6 to C14. In a subsequent step, these olefins are hydrogenated under elevated temperatures and pressures consuming hydrogen, which is a by-product of the electrocatalytic CO_2 reduction. The final product currently shows properties between conventional diesel fuel and kerosine.

3 Results and Outlook

The EcoFuel reaction sequence consists of individual units of direct air capture (DAC), electro-catalytic CO_2 reduction (ECO2R), olefin separation unit (OSU) and olefins to liquids unit (OtL). The units are based on the development work and findings from the initial project phase. After connecting and aligning all process steps into one cascade, adjustments and additional process steps in order to realize an economic and technical suitable process were suggested, to finally produce a liquid product. The carbon yield with respect to air captured CO_2 was optimized. The work included also a HAZOP analysis and a combined LCA/TEA assessment.

Reaction Cascade and Demonstration: For the realization of the reaction cascade, the individual process units were connected to define and demonstrate the overall process. The process was investigated, interfaces and scales were identified, and calculated based on mass flows of the components. Yield and conversion values are based on carbon flows (Fig. 4).

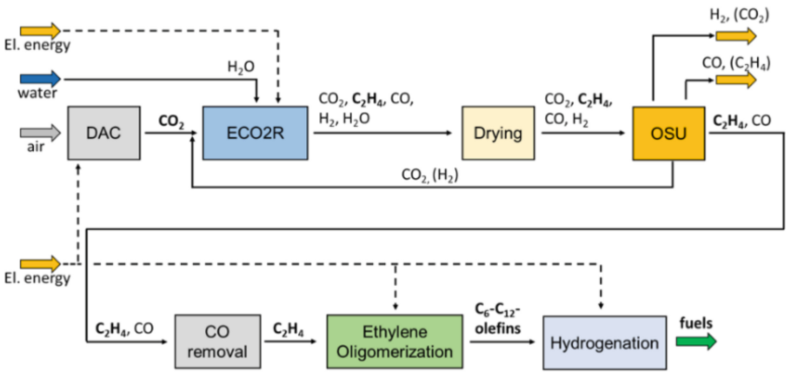

Fig. 4. Schematic picture of the EcoFuel process. Image courtesy of Fraunhofer, reproduced with permission

Following a first layout of the process scheme, adjustments were made to realize an economic and technical suitable process: (i) The unreacted CO_2 from the ECO2R has to be separated in the OSU and the CO_2 rich stream recycled back to the electrolyser, thus increasing the carbon efficiency of this process step from 9.4 % to 58 %. (ii) A drying step between the ECO2R and OSU removes the water steam. (iii) A CO removal unit takes care of the removal of CO by oxidation out of the ethylene rich stream after the OSU. (iv) Another strategy was to run the olefin oligomerization unit at higher temperatures to avoid the formation of Ni carbonyl during the oligomerization reaction.

Based on data from performed work, the concept for the reaction cascade from electrochemical CO_2 reduction to C2/C3 hydrocarbons and their further thermo-catalytic conversion into fuel products was designed. Engineering and construction of the electro chemical and thermo-catalytic systems was done and towards project end, both systems were operated under defined and industrially relevant conditions. The stability and efficiency of the processes were validated. Fuel products were handed over for analysis and assessment of properties against fuel standard specifications.

A Life Cycle Assessment (LCA) combined with a Techno Economical Assessment (TEA) was conducted to evaluate the efficiency advancements of the new process chain. At project start a meta study regarding LCA and TEA of already existing alternative fuels was conducted for determination of the baseline for comparison with the final EcoFuel product [2]. For the combined analysis, a theoretical scale up of a 1GW factory was modeled. Depending on the electricity mix the preliminary results for the LCA are between ~10 g (PV) and ~40 g (European grid mix) CO_2eq/MJ. The production cost estimation lies around 3 €/l of EcoFuel. Transport, storage and the use phase are not taken yet into consideration, as they depend on the selected geolocation, final product and its usage.

Potential applications of different EcoFuel pathway components are targeting i) Green ethylene on intermediate electrolyser size ; ii) Green fuel ; iii) Production of catalyst coated membranes (CCM) for proton exchange membrane (PEM) electrolysers. A first analysis of the charge 1 probe shows a distillation curve mainly between gasoline and diesel fuel. A further refining process could result in following products: (i) Diesel B7 (A1) (EN 590); (ii) Paraffinic diesel fuel (similar to shown HVO -A3) (EN 15940); (iii) Kerosine (C- JET A-1/JP-8); (iv) Gasoline (EN 228). However, the substitution of Kerosine or Diesel fuel has higher priority than substitution of gasoline, therefore the target is to increase the fraction of kerosine/diesel like fractions. With the project still ongoing further technical advancements are expected. A better understanding of the possible utilization of by-products and waste heat as well as the technical advancements will lead to an increase of the overall carbon efficiency alongside the whole process chain. Therefore, a further improvement in the LCA and TEA results are expected. Favoured by the promising testing results, a scaled up to 300 cm^2-active sized electrodes in a 5 cell stack operating at ~1 kW will be demonstrated towards project end.

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Sustainable Aviation Fuel (SAF) Supply

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Abstract. The aviation industry is a major contributor to greenhouse gas emissions, responsible for approximately 2% of global emissions. Sustainable Aviation Fuel (SAF), if produced from renewable or waste-based feedstocks, can reduce greenhouse gas emissions by up to 80% compared to traditional jet fuels. The push towards SAF is not the only response to the growing environmental concerns but is also a result of stringent regulations set by entities such as the EU commission. The aim of the paper is to analyse the SAF supply challenges and the current policy frameworks to incentivise supply of SAF. This analysis reviews the supply from a regulatory and industrial production policy perspective, both against the EU mandates of SAF (Refuel EU) and the proposed use of SAF (e.g., CORSIA/ETS). Further literary analysis explores why a supply gap arises. The role of technology and the need for a standardised method for measuring the life cycles of energy conversions are also important factors for increasing SAF supply. The paper concludes with policy recommendations.

Keywords: Sustainable aviation fuel · Aviation fuel policy · aviation sustainability · SAF supply · SAF production · aviation fuel

1 Introduction

Sustainable Aviation Fuel (SAF) offers a reduction of up to 80% in CO_2 emissions over the entire life cycle compared to conventional fossil-based kerosene [1]. The International Air Transport Association (IATA) has set a goal of achieving net-zero carbon emissions from aviation by 2050, and SAF is expected to play a key role in achieving this goal [2]. Hence, the global market for SAF is expected to grow significantly in the coming years, driven by the increasing demand for sustainable aviation solutions. However, there are a number of challenges that need to be addressed in order to increase the use of SAF [3].

This paper aims to analyse the SAF supply market, its challenges and the need for policy support to incentivise supply of sustainable aviation fuels. More specifically, it evaluates the relation between current policy regulations to the regulatory requirements needed for the forecasted supply of SAF, both from a mandated perspective, lifecycle analysis of the pathway and feedstock availability.

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2 Sustainable Aviation Fuels (SAF) and the Aviation Industry's Transition to a Low-Carbon Economy

There has been a lot of emphasis placed on the technological pathways for the production of SAF. By design, these SAFs are drop-in solutions, which can be directly blended into existing fuel infrastructure at airports and are compatible with modern aircraft [4] Having bigger diversity of pathways available is important as this allows SAF production from diversified feedstock. There are currently seven biofuel production pathways that are certified to produce SAF, which perform at operationally equivalent levels to Jet A1 fuel. The most widely used technologies of production that currently allow a 50% blend are:

- Fischer-Tropsch (FT): This technology converts biomass or waste into liquid fuels using a Fischer-Tropsch synthesis reactor.
- Hydroprocessed esters and fatty acids (HEFA): This technology converts vegetable oils or animal fats into liquid fuels using a hydro processing process.
- Power-to-liquid (PtL): This technology uses renewable electricity to produce hydrogen, which is then used to synthesise liquid fuels.
- Methanol to Jet technology can deliver e-jet fuel from renewable electricity, water, and CO_2 or advanced biofuel from solid biomass feedstocks.

One of the biggest challenges for the further deployment of SAF is the cost, which is currently at least twice as high as conventional jet fuel (Fig. 1). During 2022, the average SAF price estimate was around USD 2,400/t, albeit with significant differences across regions. Moreover, the cost of producing SAF varies depending on the technology used and the feedstock.

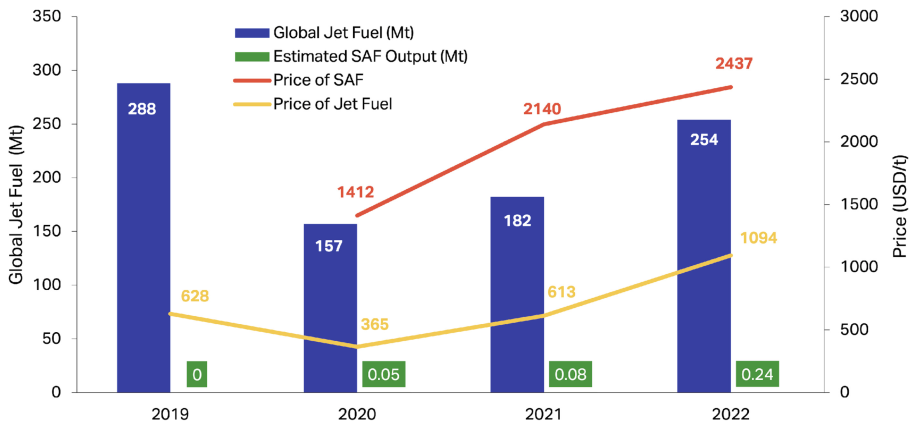

Fig. 1. Global Jet and SAF fuel price analysis 2023 [5]

The cost of FT-SAF is currently the highest, but it is expected to come down as the technology matures [5]. The cost of HEFA-SAF and PtL-SAF is lower, but they are still more expensive than conventional jet fuel. The availability of feedstock is also an important factor in the production of SAF [6]. Within a competitive market framework, increased production levels and expansion of the feedstock mix should exert downward pressure on SAF prices, progressively closing the gap to fossil-based jet fuel and easing the financial burden on airlines.

It should be noted that not all SAF are the same and the blended maximum with normal Jet fuel is currently 50%. Aromatics in jet fuel are needed for maintaining seal compatibility. A lack of aromatics can result in seal shrinkage which can lead to fuel leakage and seal failures with certain types of seals that exist in older legacy engine products, airframes, facilities and fuelling trucks. Fuel-seal compatibility is a key consideration for SAF certification and blending limits [7]. There is still a lack of clarity of research and current certification by aircraft manufacturers on the effect older aircraft and implications of going to 100% blending rates may have on the operating economics of older aircraft and the resultant maintenance costs for operators in developing or emerging economies.

It is likely that aviation will need between 330–445 million tonnes of SAF per annum by 2050. The scale-up will be a significant challenge. Up to $1.45 trillion worth of investment over the next 30 years will be required to develop this new energy system The Waypoint analysis (Table 1) provides scenarios about the SAF growth needed, but assumes that the jet fuel production plants come on line as exactly forecasted and have the required funding. This is a large assumption given the pressure from other modes of transport and the growth rate of air transport. There is still a clear production shortfall and the added factor of offtake agreements, which today are only in the forum of memorandum of understanding, raise doubts over each of these scenarios.

Table 1. Estimate of annual global SAF production (F1) from announced and in-production SAF plants and off-take agreements.

Year		2020	2021E	2023F	2024F	2025F	2027F	2028F	2030F
F1	000 tonnes	**50.4**	**80**	**1,092**	**1,877**	**3,071**	**4,914**	**6,142**	**9,213**
	M litres	63	100	1,365	2,346	3,839	6,142	7,677	11,516
	% of fuel	0.03%	0.04%	0.4%	0.6%	1%	1.5%	1.8%	2.5%
F1 high	000 tonnes	**50.4**	**95**	**1,632**	**2,806**	**4,591**	**7,346**	**9,182**	**13,773**
	M litres	63	119	2,040	3,507	5,739	9,182	11,477	17,216
	% of fuel	0.03	0.05%	0.6%	0.9%	1.5%	2.2%	2.6%	3.7%
F1 high+	000 tonnes		**166**	**2,838**	**4,879**	**7,984**	**12,774**	**15,968**	**23,952**
	M litres		208	3,548	6,099	9,980	15,968	19,960	29,940
	% of fuel		0.09%	1%	1.6%	2.6%	3.8%	4.6%	6.5%

Current production intends to follow the F1 trajectory, but the expected policy environment in the next 2–4 years aims to shift towards the F1 high trajectory at a global level. The F1 high+ trajectory is very feasible, but extra policy initiatives are needed to reach that point: recent announcements suggest this could be a possibility towards the 2030 timeframe. Practicalities of financing, construction and production timelines around the world mean getting above F1 high + is unlikely before 2030.

Another pertinent point to the SAF discourse is the entire lifecycle analysis or Life Cycle Assessment (LCA) [8]. The LCA is used to evaluate the environmental impact of

SAF production, ranging from the impact of feedstock production, sorting and refining to SAF production, transportation and use. LCA studies have shown that SAF can reduce lifecycle greenhouse gas emissions by up to 80% compared to conventional fossil-based jet fuel [9]. The environmental impact of SAF depends on the technology used for its production and the feedstock sources. To be characterised as Sustainable Aviation Fuel (SAF) qualifying oriented, a biofuel should have a LCA result that meets certain sustainability criteria [10]. The Life cycle emission value is composed of two main elements: (1) Core Life Cycle Assessment emissions, which looks at emissions related to feedstock, fuel production facilities, transportation and fuel combustion and (2) Induced land-use change (ILUC) emissions which may require additional land use in the production with feedstock.

3 Policies Related to SAF SUPPLY

SAF without policy support would remain an underinvested private sector [11]. There are various policy options that can support SAF, such as blending mandates, excise duty reductions/exemptions, research, development and demonstration funding and financial de-risking measures. For example, the Biorefinery Assistance Program, established within the Farm Bill, provides a loan guarantee for companies that turn waste into renewable jet fuel. The most important legislative measures related to biofuels in Europe are the Renewable Energy Directive (RED), the Energy Taxation Directive and the Directive on the Quality of Petrol and Diesel Fuels (FQD). The EU's recast RED II, which was ratified by the EU parliament in September 2023, sets out the EU's stricter bioenergy sustainability criteria and includes advanced biofuels & renewable fuels of non-biological origin for aviation as part of its higher renewable energy targets [12]. The regulation provides incentives, such as financial support for research and development, to promote SAF technologies and scale-up initiatives [13].

The intertwining of European and international regulations is catalysing a shift towards SAF in Europe's aviation sector. The ReFuelEU regulation requires fuel suppliers to blend a minimum share of SAF into all aviation fuel sold in the EU with the minimum share of SAF supplied at each EU airport. The minimum blend for SAF will be 2% by 2025, 6% by 2030, 34% by 2040 and 70% by 2050. The minimum share of synthetic aviation fuels will be 0.7% in 2030, 5% by 2035, 15% by 2045 and 35% by 2050.

Feedstock acquisition is a significant portion of SAF production cost and is linked to feedstock procurement, such as used cooking oils, agricultural residues, and dedicated energy crops [14]. Subsidies to the energy sector is a common practice and subsidies can support the supply of SAF (REF Efthymiou and Ryley, 2022). Direct subsidies for biofuels are only 6% (USD 38 billion) of the total amount and have mainly come from the EU (USD 11.4 billion) and the United States (USD 14.1 billion), whereas direct subsidies to fossil fuels exceeding the subsidies for renewable energy by a factor of 19 [15]. Europe needs to consider direct subsidies per output of biomass or input (indirect) subsidies for the production of biomass along with support to the full supply chain.

The technology and infrastructure needs for the scalability of SAF production processes like Hydro processed Esters and Fatty Acids (HEFA) and Fischer-Tropsch necessitate substantial investment in technology and infrastructural development [15]. There is currently a need for increased investments in research to enable 100% SAF certification without blending requirements [16] which will allow wider deployment of SAF at scale and simplify consumption by operators with respect to infrastructure requirements at airports. Policy should further support Research and Development (R&D) of new technological pathways to scale up and deliver SAF.

In addition, regulatory measures like ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), EU Emissions Trading Scheme (EU ETS) and net-zero emissions targets adopted by the aviation industry are important to support the uptake of SAF. Moreover, policy should support SAF uptake by also taxing aviation fossil fuel to close the gap and allow price parity.

4 Conclusion

This paper evaluated the SAF supply challenges to meet the forecasted supply of SAF, both from a mandated perspective, lifecycle analysis of fuel produced and from a feedstock cost. This paper concludes that central to the challenge will be price and availability of feedstock for the SAF quantities needed to fulfil current REFuelEU mandate. The paper also argued that the need for policy support and national government funding and incentives to build up SAF production infrastructure and stimulate supply.

Many challenges remain in the production and supply of SAF to meet the targets of 2050, with the price of SAF playing an important role. By a combination of scaling up of commercial PtL and SAF in general, the effect will be an improvement of lifecycle emissions performance as well as better economics for production. Despite the challenges, the outlook for the global SAF market is positive; with increasing demand for sustainable aviation solutions, combined with technological advancements and growing economies of scale, which are expected to drive the growth of the SAF market in the coming years and will help overcome price barriers in the long term.

The contribution of the paper is shedding light on the cost and production challenges that exist today and suggesting policy solutions that will allow the further deployment of SAF. More importantly, we want to highlight the need for effective policy support that considers effects like the Jevons paradox and the Green paradox of Sinn and approach decarbonisation policy in a system way.

The paper argues that further research and development into new production methods is essential for driving down production costs and discovering new, efficient production methods. By combining and prioritising these policy and incentive drivers, governments and institutions need to provide incentives for private sector participation, such as tax breaks or direct subsidies. The paper addresses the research gap of aviation decarbonisation by bringing together the policy and the free market performance of SAF highlighting the challenges.

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Analysis of Airport Infrastructure with Regard to the Use of Sustainable and Alternative Aviation Fuels

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Abstract. One approach to reducing global CO2 emissions from aviation is to improve the energy efficiency of aircraft concepts. Not only the requirements for the aircraft, but also for the infrastructure of airports are a relevant area of this research: Through the use of sustainable aviation fuels, the infrastructure of airports will inevitably adapt to new conditions. Even though airports are currently in an observer position, the required infrastructure effort must be researched at an early stage in order to provide airport customers with the infrastructure for the use of sustainable and alternative aviation fuels in good time. Exploring the feasibility of future airport requirements is the research focus of this thesis. The aim of this research is to identify future airport infrastructure measures that are required for the operation of hydrogen-powered aircraft concepts in order to be able to include necessary adaptations in airport infrastructure planning at an early stage. For this purpose, future and scenario analyses are used as methods to make an assessment based on selected criteria. It is assumed that even with a moderate future growth of hydrogen, considerable demands will have to be made on the infrastructure in general and the airport infrastructure in particular.

Keywords: sustainable air traffic · airport infrastructure · hydrogen-based aviation fuels

1 Infrastructural Requirements for the Use of Hydrogen-Based Aviation Fuel at German Airports

With the use of hydrogen-based aviation fuels, the infrastructure at airports will inevitably have to adapt to the new conditions. There are already several scientific papers in the literature that deal with the handling processes of aircraft and requirements at the airport with alternative fuels [2, 5, 8, 10]. Therefore, the focus of this research paper will be on the following research question: How airports may be impacted in terms of infrastructure when there is an increased demand for hydrogen-based aviation fuels?

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1.1 Airport Supply Infrastructure for Hydrogen-Based Aviation Fuels

In order to meet the demand for green liquid hydrogen (LH2), which is necessary for the propulsion technology of the corresponding aircraft, the supply industry must be expanded. Currently, LH2 is produced in insufficient quantities [2, 4]. The literature shows that the supply of LH2 is basically possible via three modes of transport: pipeline, rail and road [2–4, 7, 8]. The transport of LH2 on regular inland vessels is technically feasible, but is still in its infancy and there are only a few practical examples so far (e.g. H2-Ship and H2Ports), which are still in the development and test phase [11]. However, the reliability of this mode of transport depends on the seasons and high and low water levels. Delivery by road has the lowest investment costs because, in contrast to pipeline and rail delivery, no investments have to be made for the route connection. Existing road connections can be used, but new boiler handling facilities and pipeline connections are also required for the connection. However, the logistical processes for hydrogen delivery by road would be difficult to realise and uneconomical with higher demand for LH2 [4]. In addition, unloading the tanker takes longer, about 30–120 min, compared to kerosene [3].

Since the liquefaction of hydrogen is very cost-intensive, one variant could be to have it take place not at the airport but in larger, central plants. The hydrogen would then be transported to the airport in liquid form. Only in the case of pipeline supply is a liquefaction infrastructure at the airport necessary, since only gaseous hydrogen can be transported over longer distances by pipeline [5]. Throughout Europe, LH2 pipelines are being developed and planned that can also be connected to airports (e.g. European Hydrogen Backbone). As other industries could also benefit from a pipeline network, planning and development is a cross-sectoral process. However, for the deployment of this technology in the context of a national transport scenario, some problems would have to be solved. For example, in the project “icefuel”, the transport of LH2 by pipeline was investigated and a maximum transport distance of 10 km and a low maximum transport capacity of 100-200 kW were determined [8].

According to the FINE model [3], LH2 demand is covered exclusively by imports until 2050. It is assumed that LH2 production in Germany is not economical: as liquefaction is an energy-intensive process, it makes more economic sense to carry it out in export countries where the supply of renewable energy is cheaper than in Germany. For the domestic transport of LH2, rail is the most economical option under the assumptions made. Domestic LH2 transport is therefore only economically viable for transport between LH2 sources (import ports) and LH2 sinks (airports). A consideration of the last mile (e.g. transport from the freight station to the LH2 receiver) is recommended [3].

1.2 Airport Fuel Storage Infrastructure for Hydrogen-Based Aviation Fuels

The infrastructural expenses at the airport for the use of LH2 are primarily the tank farms and the filling stations. If airports want to have a similar storage capacity as for fossil kerosene, they should be able to store about three times the average daily demand [4]. For kerosene, IATA considers a storage capacity of up to four days of flight operations necessary, depending on the circumstances [11]. In the tank farm, hydrogen is stored in liquid form by isolating and deep-freezing the LH2. The single-phase storage of LH2 at the airport has advantages over the storage of H2 for economic and safety reasons, especially to avoid boil-off effects (escaping gas due to evaporation) [8]. NASA currently has the largest cryogenic storage tank in the world. It is located in Florida and has a capacity of 270 tons of liquid hydrogen. JAXA in Japan has a storage container with a capacity of 38 tons. Future liquid hydrogen tanks are expected to be about 13 times larger than NASA's existing tank. These new tanks will be able to safely store up to 3,500 tons of hydrogen [12]. According to current knowledge, safety regulations have not yet been fully clarified, e.g. whether hydrogen tank farms should be built at a different distance from airport operations compared to kerosene.

1.3 Airport Distribution Infrastructure for Hydrogen-Based Aviation Fuels

For the distribution of hydrogen to the aircraft, an Airfield Tanker (FTKW) on the one hand and an LH2-Underground Pipeline System (UPS) with the use of dispensers on the other hand could be used at the airport in the future. Which of these two distribution systems is chosen depends on the airport's daily fuel requirements [8]. At the beginning of the integration phase of LH2 as fuel at airports, the FTKW are considered more advantageous up to a certain demand. However, especially in the long term, UPS are more advantageous at hub and major secondary airports serving long-haul routes, as each FTKW can only carry a certain amount of LH2 (about 3–5 tones) [5, 8]. As a result, too many FTKWs would be needed at hub and larger secondary airports, making airport turnaround processes no longer economical and safe due to space constraints [1, 8]. The use of a UPS or FTKW also has an effect on the possibility of levying various charges. For LH2 short- and medium-haul aircraft (e.g. DLR EXACT project), a range of up to 2,777 km requires approximately up to 31 m^3 of LH2. With a capacity of a FTKW of up to 70 m^3 LH2 (5 tons), an LH2 FTKW, similar to a kerosene FTKW, can refuel up to two medium-haul or several short-haul routes with one load from the LH2 tank farm, depending on the flight route [5, 8]. Due to the limited pressure and pumping capacity, an LH2-UPS can only be about two kilometers long, so several pipelines would have to run from the tank farm to the individual refueling positions [8]. In addition, a recovery pipeline is needed at the airport to transport the gases escaping during refueling to an intermediate storage facility back to the tank farm [4, 5]. The quantity-independent refueling time of LH2 is, depending on the connection, similar with the Clean Break Disconnect (6 min) as with kerosene (5 min), with the Johnston Disconnect (9 min) it is almost twice as long. It is still unclear which connection will be used. However, LH2 has a significantly higher energy flow rate during refueling, so less time is needed for volume-dependent refueling [5, 8].

2 Analysis of the Effects of Increased Demand for Hydrogen-Powered Aircraft on German Airports

In order to determine the possible effects of the demand for hydrogen-powered aircraft at airports, the data from the DLR's Air traffic forecast & LH2 demand model were used as the basis for the analysis. The 25 largest commercial airports in Germany were analysed for infrastructure bottlenecks in terms of supply, fuel storage and distribution if hydrogen were to develop as a propulsion alternative for aircraft in a moderate continuous scenario (Table 1). The annual demand was converted to a daily consumption (without considering peaks on weekdays or holiday periods). In order to be able to better estimate these values, the filling quantity of the currently largest tanker truck for liquid hydrogen with four tones was used as a kind of "currency". This should make it clear how the demand could be mapped with the means of transport by truck or by road.

Table 1. Future Airport Infrastructure Analysis – German Airports.

GERMAN AIRPORTS Top 25		Liquid Hydrogen in tons														
		2040					2045					2050				
	Code	Forcast	per day	# Trucks	Stock	# Tanks	Forcast	per day	# Trucks	Stock	# Tanks	Forcast	per day	# Trucks	Stock	# Tanks
MUNICH	MUC	12,380	33.9	8	136	**1**	72,759	199.3	50	797	**3**	124,749	341.8	85	1,367	**5**
FRANKFURT	FRA	12,328	33.8	8	135	**1**	69,636	190.8	48	763	**3**	117,007	320.6	80	1,282	**5**
BERLIN	BER	6,950	19.0	5	76	**1**	39,630	108.6	27	434	**2**	67,266	184.3	46	737	**3**
DUESSELDORF	DUS	5,421	14.9	4	59	**1**	31,525	86.4	22	345	**1**	53,806	147.4	37	590	**2**
HAMBURG	HAM	4,189	11.5	3	46	**1**	24,021	65.8	16	263	**1**	40,853	111.9	28	448	**2**
STUTTGART	STR	2,449	6.7	2	27	**1**	14,127	38.7	10	155	**1**	23,604	64.7	16	259	**1**
COLOGNE	CGN	1,944	5.3	2	21	**1**	10,586	29.0	7	116	**1**	17,677	48.4	12	194	**1**
HANNOVER	HAJ	1,198	3.3	1	13		6,719	18.4	5	74	1	11,293	30.9	8	124	**1**
NUERNBERG	NUE	589	1.6	0.40	6		3,507	9.6	3	38	1	5,981	16.4	4	66	1
BREMEN	BRE	527	1.4	0.36	6		2,961	8.1	2	32	1	4,919	13.5	3	54	1
DRESDEN	DRS	418	1.1	0.29	5		2,662	7.3	2	29	1	4,569	12.5	3	50	1
LEIPZIG	LEJ	299	0.8	0.20	3		1,743	4.8	2	19	1	2,972	8.1	2	33	1
MUENSTER/OSNA.	FMO	180	0.5	0.12	2		1,064	2.9	1	12		1,763	4.8	1	19	1
DORTMUND	DTM	137	0.4	0.09	2		538	1.5	0.37	6		758	2.1	1	8	
KARLSRUHE	FKB	111	0.3	0.08	1		605	1.7	0.41	7		1,038	2.8	1	11	
SAARBRUECKEN	SCN	103	0.3	0.07	1		583	1.6	0.40	6		930	2.5	1	10	
FRIEDRICHSHAFEN	FDH	88	0.2	0.06	1		574	1.6	0.39	6		1,003	2.7	1	11	
PADERBORN	PAD	70	0.2	0.05	1		317	0.9	0.22	3		499	1.4	0.34	5	
WESTERLAND	GWT	37	0.1	0.03			239	0.7	0.16	3		415	1.1	0.28	5	
HAHN	HHN	34	0.1	0.02			100	0.3	0.07	1		131	0.4	0.09	1	
MEMMINGEN	FMM	22	0.1	0.02			105	0.3	0.07	1		171	0.5	0.12	2	
WEEZE	NRN	22	0.1	0.02			50	0.1	0.03	1		58	0.2	0.04	1	
LAAGE	RLG	17	0.05	0.01			93	0.3	0.06	1		145	0.4	0.10	2	
ERFURT	ERF	13	0.04	0.01			71	0.2	0.05	1		107	0.3	0.07	1	
MANNHEIM	MHG	10	0.03	0.01			71	0.2	0.05	1		145	0.4	0.10	2	
		49,536.4	135.7	33.9	541.1	6.0	284,286.9	778.9	196.1	196.1	16.2	481,859.5	1,320.2	330.0	5,280.7	24.1

Code : IATA Airport Code Airports in gray color : Airports with railway connetion per day : Average of 365 days; no peaks
Trucks : Number of trucks with a loading capacity of four tons of LH2, which are necessary to cover the daily requirement (rounded up or decimal places)
Stock : Storage capacity for LH2 for up to four days of flight operations (Liquid Hydrogen in tons).
Tanks: How many tanks with the capacity between 38 und 270 tones would be need to cover the four day

Source: Data based on the "DLR - Air traffic forecast & LH2 demand modelling Data from DLR Institute of Air Transport and Airport Research 2022.

The first result of the analysis of the data is that there are two groups: One group of airports (lower range) gets by with less than one four-ton tanker fill per day, per week or even per month. The higher range airports have significantly higher to very high demand. The last group grows steadily over time and could overload the framework of the road mode from 2045 onwards under the given conditions: FRA and MUC would need 80–85 tankers per day from 2050 onwards. Other ways would have to be found for these cases. Be it through pipeline supply or by connecting to the rail network. In the latter case, only 4 airports (table: marked grey) are currently connected to the rail network. It should be noted that the rail connections and the required facilities for passenger and freight transport differ significantly and that here no 1:1 implementation are possible and structural adjustments are necessary. Several German airports are located near inland waterways and are connected to inland waterways via rivers or canals. This makes it possible to transport not only goods and freight between airports and inland ports, but also LH2 by water. This is particularly important for the transport of LH2 arriving by sea. Almost all airports in the top 15 can boast proximity to an inland port.

The second result can be seen when applying the IATA guidelines for the minimum requirements for airport kerosene stocks, which stipulates that fuel should be kept in stock for up to 4 days based on the size of the airport. If you transpose this 1:1 to the Liquid Hydrogen, then this shows a bottleneck in the infrastructure at the airport: For the year 2045 alone, this would be a reserve of almost 800 tons for the FRA and MUC airports. In 2050 up to 1,400 tons. If you take the currently largest LH2 storage tank in the world (NASA) with a capacity of 270 tons, then at least three of them would have to be built in FRA and MUC by 2045 and two more each by 2050. The open space requirements for above-mentioned LH2 tanks is approximately 2,300 m2 [11] - without considering the safety distances between the tanks - this would be an additional space requirement at the MUC and FRA airports with each 11,500 m2 by 2050.

The third result can be seen when looking at the total numbers and their increase from 2045 onwards: The increase figures for the forecast hydrogen consumption at airports are remarkably high and would indicate an active increase in the use of hydrogen as an energy source for airport operations. These increases will depend on many factors, including technological advances, political decisions, environmental goals and economic factors. The availability and efficiency of hydrogen technologies, especially in aviation, are crucial. Advances in hydrogen production, storage and use could promote the use of hydrogen as fuel for aircraft and airport vehicles. If the predicted increases in hydrogen consumption at airports materialize, this would pose significant challenges for the airport infrastructure. The production of hydrogen in sufficient quantities and its reliable supply at airports are crucial. This requires significant hydrogen production, storage and distribution infrastructure that must be operated safely and efficiently.

Increased use of hydrogen as fuel may impact capacity requirements at airports. Airport operators would have to ensure that they can cope with the increasing demand for hydrogen services. These challenges are not insurmountable, but they require careful planning, investment in research and development, and collaboration between airport operators, aircraft manufacturers, energy companies, governments and other relevant stakeholders. The introduction of hydrogen as an energy source in aviation would be an important step towards reducing the industry's environmental impact, but it requires a comprehensive and coordinated effort.

3 Summary and Outlook

The evaluation of the literature and the analysis of our own data have shown that some problems in the provision of liquid hydrogen for airports need to be solved by 2045: If delivery with road tankers would still be sufficient for regional and smaller secondary airports, larger ones should be used Secondary airports should consider having the hydrogen delivered via rail transport due to the higher demand, as larger quantities can be transported more safely and economically via rail transport. For hub airports, a pipeline supply to the airport would certainly be advantageous, as the logistical processes via rail and road transport would no longer be feasible at a certain scale. The chances of inland shipping still need to be clarified, but are obvious, as large quantities of LH2 will arrive in Germany by sea in the future. The installation of hydrogen infrastructure may require additional space at airports. Airports would need to allocate land and facilities for hydrogen fueling stations, storage, and pipeline infrastructure. Building or retrofitting hydrogen fueling infrastructure, storage facilities, and pipeline systems can be costly. Airports will need to allocate funds for the initial construction and ongoing maintenance of this infrastructure. Airports need to invest in renewable energy infrastructure, which can be costly upfront but could offer long-term environmental and cost benefits. Complying with safety and environmental regulations related to hydrogen fuel handling may require investments in compliance measures, documentation, and reporting. Airports may explore mechanisms for cost recovery, such as charging airlines or passengers a premium for using hydrogen-based fuels, to offset some of the infrastructure and operational expenses. It is important to emphasize that the use of hydrogen as a fuel in aviation is still in its early stages and it will require significant effort and investment to establish this technology on a large scale. It will require close collaboration between industry, governments and other stakeholders to make the vision of hydrogen-based aviation a reality. Furthermore, the most likely scenario for airports in the future will be a diversified mix of different sustainable fuel options. A follow-up study will show how the infrastructure and supply chain requirements for each fuel type may differ and how these different systems can be integrated.

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Performance Assessment of an Advanced Hybrid System Between SOFC and ICE to be Applied Onboard a Short-Distance Ferry

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Abstract. It is imperative to research innovative energy systems to maximize energy efficiency and decarbonize the maritime sector because the International Maritime Organization has set two milestones in 2030 and 2040 to reduce greenhouse gas emissions with an ultimate decarbonization target of zero emissions by 2050. This paper investigates an advanced integration between a solid oxide fuel cell (SOFC) and an internal combustion engine (ICE) targeting a passenger ferry operating on short-sea navigation as a case study with a rated power of 750 kW. The paper aims to model the hybrid system by using dedicated in-house software developed by the authors' research group to assess the system performance by exploring the system efficiency, fuel consumption, and carbon dioxide (CO_2) emissions and conducting a sensitivity analysis for operating parameters. The results show that an efficiency improvement of 12% over the marine gas engine, with 32.4% fuel savings, and 29.7% CO_2 emissions savings, is possible by maintaining the current density at 5000 A/m^2, fuel utilization at 80% and using a 50–50 power split between SOFC and ICE.

Keywords: solid oxide fuel cell · internal combustion engine · natural gas · hybrid system · short-distance ferry

1 Introduction

Despite marine transportation being a reliable method of traveling between nations inside and outside the European Union (EU), it contributes by roughly 3–4% to the EU's overall carbon dioxide (CO_2) emissions. In order to reduce CO_2 emissions and meet the decarbonization objectives, the EU has suggested including ship emissions in its emission trading system (ETS) [1]. Moreover, the International Maritime Organization (IMO) pushed for the reduction of CO_2 emissions from ships by setting up a strategy targeting the utilization of advanced energy systems and alternative fuels to represent at least 5% of the energy used by ships by 2030 to achieve a reduction of greenhouse gas emissions of 20% and striving for 30% compared to 2008 levels, while the ultimate decarbonization target of the recent IMO strategy is to reach net zero GHG emissions by 2050 [2].

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There are different technical and operational measures [3] that can be used to achieve these targets, the utilization of alternative fuels [4], and advanced energy systems onboard ships [5] are considered the best options to be used for achieving IMO reduction targets.

Natural gas is considered a transition fuel for the maritime sector as it has many advantages over other fuels [6] and is the only competitive one to the conventional fuel (diesel fuel) because it has the following characteristics; has many infrastructure sites available globally, lower costs than other alternative fuels, higher energy density, has the possibility to power the marine gas engines and fuel cells [7]. Regarding advanced energy systems, fuel cell systems attract increasing attention as possible energy system onboard ship due to their high-efficiency levels compared to diesel engines, and low exposure to pollutants as it is powered by clean fuels [8].

The authors made a comprehensive review of the application of fuel cells onboard ships from different perspectives as shown in [8], it is concluded that the solid oxide fuel cell (SOFC) is more beneficial than the proton exchange membrane fuel cell (PEMFC) in terms of fuel flexibility as it can be powered by many fuels such as natural gas and has the possibility to be integrated with internal combustion engines (ICE) thanks to their high operating temperature.

Inspired by these findings, the current study proposes the integration of SOFC with ICE as a novel marine propulsion system for a short-distance ferry fueled by natural gas. Moreover, to increase the efficiency of the hybrid system, it is proposed to recirculate the anode off-gas (AOG) to be blended with natural gas and used in the ICE to deliver additional electrical power. The paper aims to investigate the performance of the innovative system by conducting a parametric/sensitivity analysis of crucial operating parameters of the SOFC system and study their effects on the hybrid system efficiency, fuel consumption saving, and the amount of CO_2 abated when compared with a conventional marine gas engine (MGE).

2 Methodology

2.1 Research Approach

The aim of the current research study will be investigated by the methodology presented in Fig. 1.

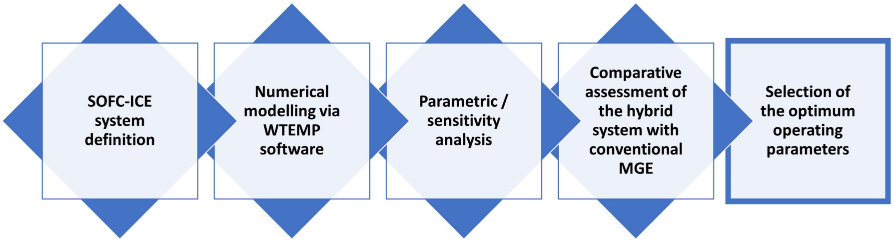

Fig. 1. Framework of the research methodology

The research approach has different steps starting with defining the required electric power from the system with identifying the main control/input parameters. Then, the second step is to model the hybrid system between SOFC and ICE using in-house software to capture the system performance. The third step is to conduct a parametric/sensitivity analysis of the system under different sensitivity parameters such as fuel utilization, and current density. This sensitivity analysis will be enriched by conducting a comparative assessment between the hybrid system and a conventional MGE operated by natural gas that is available in the market. Finally, based on the performance analysis results, the optimum operating parameters can be defined.

The thermo-economic analysis of the hybrid system is performed by using an in-house software called WTEMP (Web-based Thermoeconomic Modular Program) which was developed by the authors' research group at the University of Genoa. The user who uses WTEMP software can construct a complex system like the investigated one thanks to its expanded library which contains more than 90 modules.

2.2 Hybrid System Configuration

The description of the hybrid system between SOFC and ICE is presented in Fig. 2. There are two fuel sources in the proposed configuration, a methane source for feeding the SOFC after the reforming operation, and a natural gas source for feeding the ICE after the blending process with AOG. Since realistic SOFC systems use a methane pre-reformer to reduce the possibility of carbon deposition and extreme temperature differences inside the SOFC's cells, the proposed configuration has a methane pre-reformer that feeds by high-temperature methane and steam to produce the reformed fuel required for SOFC operation.

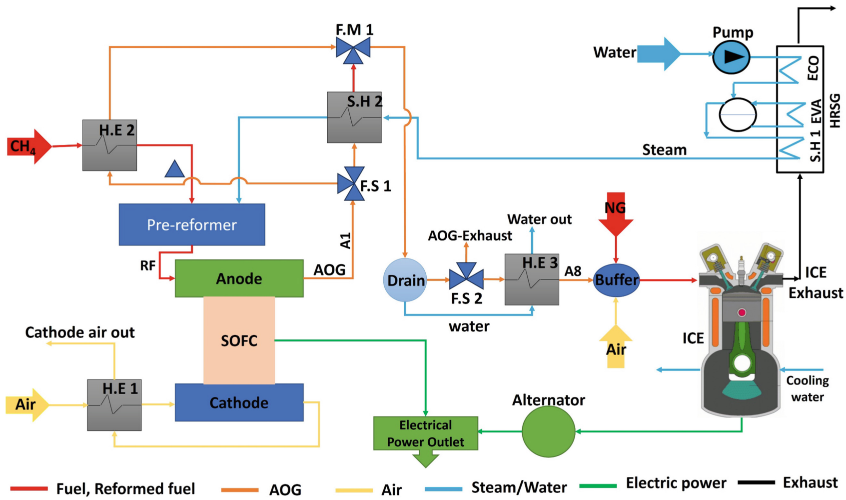

Fig. 2. The layout of integration between SOFC and ICE in WTEMP software.

The SOFC's anode and cathode sides are fed by reformed fuel (RF) and oxygen from the air, respectively to produce the electrical power. The high-temperature AOG is proposed to be circulated into two streams to heat up the methane and steam before they are mixed again into a flow mixer (F.M 1). The composition of AOG is a mixture of hydrogen, carbon monoxide, carbon dioxide, and water vapor, the latter ingredient (water vapor) is proposed to be removed by circulating the AOG into a drainer before employing AOG in the ICE which can encounter instability issues with the existence of vapor. Moreover, there is a flow separator (F.S2) to stabilize the volumetric percentage of AOG at 30% of the total fuel delivered to the ICE. The AOG is cooled down through a heat exchanger (H.E3) before mixing with natural gas in the buffer. The ICE's exhaust gas is employed as a heat source inside a heat recovery steam generator (HRSG) to produce the steam that is circulated into the pre-reformer.

There are some control parameters for the SOFC system have been fixed during the parametric analysis, such as the AOG/NG blending ratio is constant at 30–70%, the temperature of reformed fuel and air at the inlet of SOFC is kept constant at 800 °C, steam to carbon ratio and conversion ratio of the pre-reformer are kept constant at 2 and 10%, respectively. While the efficiency and pressure drop of different heat exchangers are kept constant at 85% and 0.01 bar, respectively.

The electrical power generated from the hybrid system is kept constant at 750 kW during the parametric analysis that is proposed to be employed as a power generation system onboard a small passenger ferry like what has been investigated by the authors in [5]. The comparative assessment is proposed to be done by using two MGEs [9] operated at 75% load factor with a power rating, efficiency, and fuel consumption equal to 750 kW, 32.1%, and 0.059 kg/s, respectively. The efficiency of SOFC, ICE, and the hybrid system can be calculated as shown in Table 1.

Table 1. Formulas for the calculation of the efficiency of different components in the study

Component	Formula	Equation number
SOFC	$\eta_{SOFC} = \frac{P_{SOFC}}{\dot{m}_{rf} \times LHV_{rf}}$	(1)
Standalone ICE	$\eta_{I-ICE} = \frac{P_{ICE}}{\dot{m}_{AOG-NG} \times LHV_{AOG-NG}}$	(2)
Integrated ICE	$\eta_{I-ICE} = \frac{P_{ICE}}{\dot{m}_{AOG-NG} \times LHV_{AOG-NG} - \dot{m}_{H_2} \times LHV_{H_2}}$	(3)
Hybrid system	$\eta_{SOFC} = \frac{P_{SOFC}+P_{ICE}}{\dot{m}_{CH_4} \times LHV_{CH_4} + \dot{m}_{NG} \times LHV_{NG}}$	(4)

3 Results and Discussions

The performance of the hybrid system is proposed to be assessed by changing operating/input parameters of the SOFC system like fuel utilization and current density.

3.1 Effect of Current Density on the Performance of the Hybrid System

To analyze the effect of the current density on the hybrid system's performance, the current density is proposed to be varied from 3000 A/m^2 to 7000 A/m^2, with an increment of 1000 A/m^2 while keeping the fuel utilization fixed at 80%. The results of efficiency and power outputs for SOFC-ICE hybrid system at the simulated current densities are shown in Fig. 3.

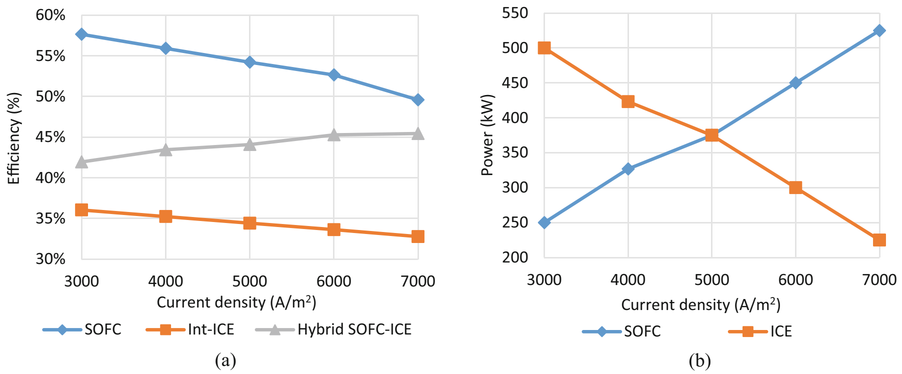

Fig. 3. Effect of the current density on the SOFC-ICE system (a) efficiency (b) output power

The results showed that the SOFC produces more power by increasing the current density which causes a rise in the SOFC's fuel consumption, therefore, the efficiency of SOFC is reduced as shown in Fig. 3 (a). On the other hand, the ICE's power is reduced by increasing the current density as shown in Fig. 3 (b) to keep the total output power of the hybrid system at 750 kW. Moreover, the integrated ICE's efficiency is reduced proportionally to its low power output at high current densities. Regarding the hybrid system's efficiency, it increases from 42% at a current density of 3000 A/m^2 to 45.5% at a current density of 7000 A/m^2 because SOFC is contributed by a higher share than ICE at the high current densities.

Additionally, the high contribution of SOFC in the power output of the hybrid system leads to a significant reduction in fuel consumption when compared with the conventional MGE. The fuel and CO_2 savings when compared to the hybrid system with conventional MGE are about 26.2% and 23.3% at a current density of 3000 A/m^2, respectively while it is increased to about 38% and 36.3% at a current density of 7000 A/m^2, respectively.

Although the high efficiency of a hybrid system can be achieved at high current density, the performance degradation is expected to be accelerated due to high voltage loss at high current densities densities [10]. Therefore, the optimum performance is expected to be achieved at 5000 A/m^2 in which the efficiency of the hybrid system is 44.1% with power output of 375 kW for each of SOFC and ICE.

3.2 Effect of Fuel Utilization on the Performance of the Hybrid System

Motivated by the results achieved in Sect. 3.1, the power split between SOFC and ICE is kept constant at 50% (375 kW) for each of them during the simulation, moreover, the current density is fixed at 5000 A/m^2 with keeping the other control parameters constant. In the sensitivity analysis, the fuel utilization is proposed to be varied between 70% and 85%, with an increment of 5%. The target rated power from SOFC (375 kW) at different fuel utilizations is controlled by changing the mass flow rate of pure methane entering the SOFC system. The efficiency of different components in different fuel utilization cases is shown in Fig. 4.

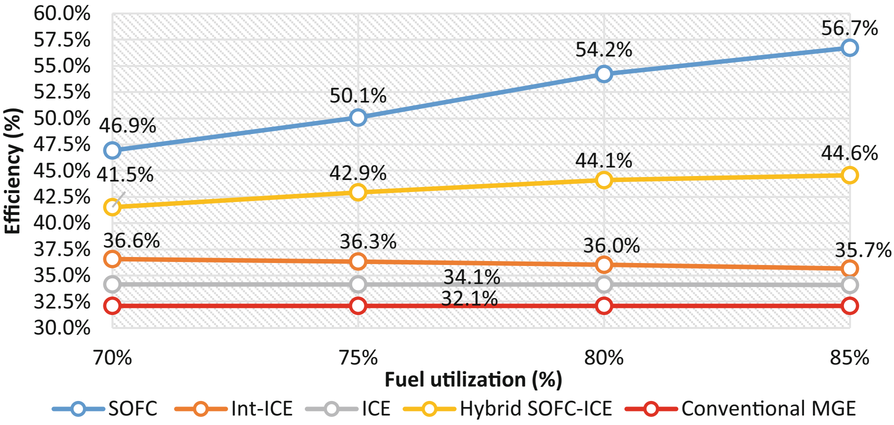

Fig. 4. Effect of fuel utilization parameter on the efficiency of SOFC-ICE hybrid system.

The results show that excluding the contribution of hydrogen's energy in the AOG-NG blend inside ICE increases the efficiency of integrated ICE compared with standalone ICE which includes the hydrogen's energy contribution in its evaluation. This improvement in efficiency is equal to 2.4% by using FU of 70% while this improvement reduces to 1.6% by using FU of 85%. Moreover, the efficiency of integrated ICE in the hybrid system is better than conventional MGE with a maximum improvement of 4.5% at FU of 70% due to the utilization of hydrogen in lieu of natural gas as fuel which improves the combustion quality. On the other hand, the increment in FU percentage increases the percentage of CO_2 flow rate to be more than the hydrogen flow rate inside AOG as shown in Table 2, therefore, the efficiency of integrated ICE decreases from 36.6% (FU = 70%) to 35.7% (FU = 85%).

The result of thermodynamic analysis proves the fact of enhancement of SOFC efficiency by increasing fuel utilization as the maximum SOFC's efficiency is 56.7% at FU of 85% while the SOFC's efficiency is 46.9% at FU of 70%. Furthermore, the hybrid system's efficiency is increased by increasing the fuel utilization because the improvement in SOFC efficiency compensates for the reduction in the efficiency of the integrated ICE. The integration between SOFC and ICE enhances efficiency over the traditional MGE in the range of 9.4% to 12.5% depending on the value of FU as the maximum improvement is achieved by using FU of 85%.

Besides the investigation of system efficiency, there are other performance indicators that can be assessed such as fuel consumption of the hybrid system and the quantity of CO_2 emissions generated which are evaluated as presented in Fig. 5.

Table 2. Flow rates expressed in m^3/hour for hydrogen and carbon dioxide contained in AOG at the exit of SOFC anode (A1) and their values at AOG directed into ICE (A8)

Fuel utilization	H_2 at A1	CO_2 at A1	H_2 at A8	CO_2 at A8
70%	84.05	65.16	26.01	20.17
75%	63.32	61.87	23.61	23.07
80%	45.96	59.28	20.65	26.64
85%	32.56	59.18	17.27	31.39

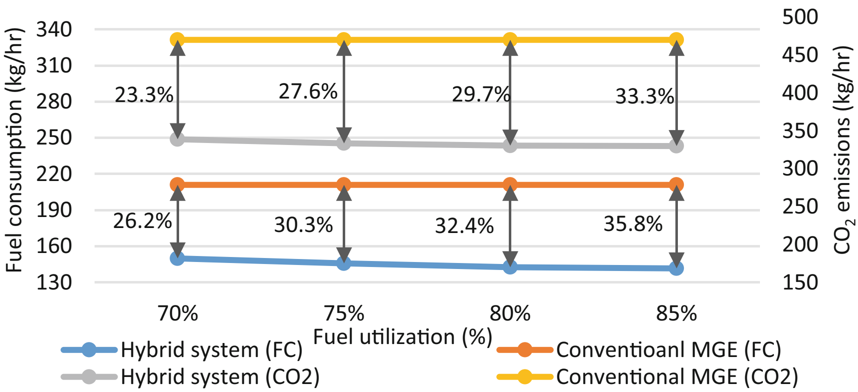

Fig. 5. Effect of fuel utilization parameter on the fuel consumption (FC) and CO_2 emissions of SOFC-ICE hybrid system in comparison to conventional marine gas engine.

The fuel consumption of a hybrid system is about 150 kg/hr when using FU of 70%, this consumption reduces to 141.6 kg/hr at FU of 85%. When comparing this consumption with its counterpart at conventional MGE, the fuel consumption of the hybrid system is lower than MGE by about 35.8% at FU of 85%. In addition, the quantity of CO_2 generated is 339 kg/hr at FU of 85%, while it reduces to 330 kg/hr at FU of 85% (this value is lower than CO_2 emissions generated by using MGE by about 33.3%).

The results proved that to achieve safe operation, high efficiency, and a favorable ratio of H_2 and CO_2 in the AOG-NG mix for better performance of ICE, the fuel utilization of 80% is suitable for the hybrid system between SOFC and ICE.

4 Conclusions

The performance analysis of an integrated hybrid system between SOFC and ICE has been assessed for maritime applications by calculating the efficiency, fuel consumption and CO_2 emissions produced by the system. The SOFC-ICE hybrid system is based on a parallel integration between them in which the anode-off gas from SOFC is proposed to be utilized as an input fuel to ICE after removing water vapor and blending it with natural gas. The main conclusions are shown as follows:

(a) The performance of the SOFC-ICE system is enhanced by increasing the current density, although there is an inverse proportion between the efficiency of both SOFC and integrated ICE with the increment in current density due to the high-power contribution from SOFC at high current density.
(b) The best performance is anticipated to be attained at the current density of 5000 A/m^2, where the efficiency of the hybrid system is 44.1% and the power split of 50% (375 kW) for each SOFC and ICE. Moreover, there is a saving in fuel consumption and emitted CO_2 emissions equal to 32.4% and 29.7% respectively when compared with conventional MGE.
(c) By increasing the fuel utilization in SOFC, the flow rate of CO_2 is increased in the AOG that is used in ICE, therefore, the integrated ICE efficiency is marginally reduced. On the other hand, the SOFC's efficiency has a significant increasing trend that led to an increase in the hybrid system efficiency at high fuel utilization.

The findings show that a fuel utilization of 80% is advantageous with maintaining the current density at 5000 A/m^2 and utilizing a 50–50 power split between SOFC and ICE in order to achieve considerable efficiency, safe operation, and low CO_2 emissions.

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Exnovations in Energy and Mobility in Europe: Impacts on and Engagement of Vulnerable Groups

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Abstract. Exnovation refers to processes of destabilization, decline, and phase-out of carbon-intensive industries, technologies, business models, and practices, as well as those that create other systemic sustainability challenges. Implementing successful low-carbon transitions across Europe that are socially fair, just, and effective is challenging. While transition policies are usually promoting innovation and diffusion of technological advancements, less focus is dedicated to systemic decarbonization and phasing-out of non-sustainable technologies, materials and practices. Phase-out policies and their implementation supporting a just-low-carbon transition are fundamental to achieve current climate change goals. Nevertheless, the engagement of and the impacts on citizens exposed to most severe effects of transition policies remain underexplored, but are crucial to avoid reinforcement of existing injustices, such as inequitable distribution of costs, or non-inclusive decision-making processes. Therefore, in this paper we explore 27 past and present initiatives related to transition policies in the mobility and energy sector across EU, Canada and Australia to understand their undesired (negative) impacts, affected vulnerable groups and their participation in the decision-making process. This study stems from TANDEM, a Horizon Europe project, that is utilising an innovative transdisciplinary approach to assess and mitigate negative impacts on citizens at risk of vulnerability due to implementation of low-carbon transition policies. Our analysis shows that although it depends on the type, location, and scale of the transition initiatives, vulnerability factors are often related to level of education, level of income, age, gender, house ownership, ethnicity, job sector, geographic location, migration background, and disability. Unfortunately, there is a lack of understanding, awareness or recognition among policy and decision makers when it comes to vulnerability factors and undesired impacts

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associated with transition policies and initiatives. One-third of the analysed initiatives did not even identify any vulnerable groups and only less than half of the initiatives undertook some effort to engage citizens or account for concerns of vulnerable groups, while only two (out of 27 initiatives analysed) allowed vulnerable groups to take part in the decision-making process. This lack of analysis of inequalities and vulnerabilities prior to implementing low-carbon transition initiatives and policies can not only lead to lower acceptability of these initiatives, but also can cause serious negative consequences, such as deepening inequalities and increasing energy and mobility poverty of certain societal groups. Effective addressal of issues related to fairness and justice are imperative for successful implementation of transition policies.

Keywords: Exnovation · Transition policies · Vulnerable citizens

1 Introduction

Exnovation refers to processes of destabilization, decline, and phase-out of carbon-intensive industries, technologies, business models, and practices, as well as those that create other systemic sustainability challenges. Justifiably exnovation is a pivotal element for the energy and mobility transition (Graaf, et al., 2021). While transition policies are usually promoting innovation and diffusion of technological advancements, less focus is dedicated to systemic decarbonization and phasing-out of non-sustainable technologies, materials and practices. However, phase-out policies and their implementation supporting a just transition are fundamental to achieve current climate change goals. At the same time, implementing successful mobility and energy transitions across Europe that are socially fair, just, and effective is challenging as exnovations can increase the social vulnerability of actors involved in and affected by transitions, ranging from individuals (e.g. belonging to low-income households and social housing residents) to entire regions or states (Bouzarovski, et al., 2017). Implementing such transition policies can potentially worsen social and material inequalities, create new risks and uncertainties for energy security and access to daily activities (Martiskainen, et al., 2021; Hoggett, et al., 2014). Nevertheless, the needs of and the impacts on citizens exposed to most severe effects of transition policies remain underexplored, but are crucial to avoid reinforcement of existing injustices, such as inequitable distribution of costs and benefits, urban-rural divide, non-inclusive decision-making processes to name a few (Sovacool, Hook, Martiskainen, & Baker, 2019). Therefore, in this paper we explore 27 past and present initiatives related to transition policies in the mobility and energy sector across EU, Canada and Australia to understand their undesired (negative) impacts, affected vulnerable groups and their participation in the decision-making process. This study stems from TANDEM, a Horizon Europe project, that is utilising an innovative transdisciplinary approach to assess and mitigate negative impacts on citizens at risk of vulnerability due to implementation of transition policies. Further the aim of the project is to develop inclusive and just transition pathways by involving affected (vulnerable) citizens, public authorities, private sector and other relevant stakeholders.

2 The Concept of Vulnerability

Vulnerability is a multi-disciplinary concept studied from various perspectives including sociology, economics, political science, philosophy, and humanities. Vulnerability refers to a condition where individuals or groups are at a higher risk of being hurt or harmed. It can be framed within the theory of risk society, where modern societies are exposed to various tangible and uncertain threats (Beck, 1992; Giddens, 1990; Giddens, 1991). Vulnerability is influenced by factors like marginalization and limited influence over decision-making processes (Giddens, 1991; Bauman, 2013). It is shaped by social and political structures and systems of power, with systems of oppression amplifying vulnerability for certain groups, often linked to poverty, race, ethnicity, and gender (Fineman & Grear, 2013). From a socio-economic perspective, vulnerability is combined with economic and financial factors like income insecurity, unemployment, age, level of education, religion and limited access to resources (Alwang, Siegel, & Jorgensen, 2001; Papantonis, et al., 2022; Alonso-Villar & Del Río, 2008; Blake, 2013). Vulnerability when approached from a legal perspective, emphasizes human rights, dignity, and the role of governments and social actors in ensuring equal opportunities and protection (Stiglitz, 2012). Therefore, vulnerability is a dynamic and relational concept influenced by social, political, economic, cultural, and environmental factors. It is important to consider the complex interplay between these factors and address them to fully explain vulnerability. In the context of the TANDEM project and in this study, initiatives have been explored with the conceptualization that vulnerability is not intrinsic, rather it is a result of biophysical factors, power relations, and socio-economic position of an individual or a group with respect to one phenomenon or the other (Mackenzie, Rogers, & Dodds, 2014). When dealing with exnovations, it is important to consider vulnerability as a multi-dimensional concept that encompasses exposure, sensitivity, and the ability to cope with and recover from impacts of exnovations and related transition policies (Turner, et al., 2003; Emmel & Hughes, 2014).

3 Methodology

Given the focus of the study, the exploration started with an extensive literature review of the concept of vulnerability and vulnerabilities associated with transition policies. Then 27 relevant past and present transition initiatives at local, regional, national and international level in the energy and mobility sector affecting urban and rural populations were identified for further analysis. Although initiatives were selected from different European countries, some initiatives were also selected at EU level and from Canada and Australia to make the study more robust and to get some international perspective. These 27 initiatives demonstrate the variety and intricacy of transitions to a low-carbon and sustainable society. Furthermore, Table 1 shows the list of initiatives that were selected. Information on these initiatives were collected using literature review, interspersed document analysis and media analysis. Then the information collected were analysed, and 4 semi-structured interviews were carried out with initiative promoters to (i) understand how these initiatives have inflicted negative or undesired effects on certain parts of society, (ii) identify affected (vulnerable) groups, and (iii) if and how vulnerabilities, needs and participation of these groups have been considered in the decision-making process related to formulation and implementation of these initiatives.

Table 1. List of analysed past and present transition initiatives

Item no.	Name of the initiative and location
1	A just and fair transition for Canadian coal power workers and communities. (Canada)
2	Citizens' Jury on carbon neutral road transport. (Finland)
3	Latrobe Valley Authority - manage the just transition associated with the closure of the Hazelwood coal fired power plant. (Australia)
4	Germany's hard coal mining phase-out. (Germany)
5	Just Transition Mechanism. (EU)
6	Energieplan Innsbruck. (Austria)
7	DoppelPlus Gemeinsam gegen Energiearmut - Together against energy poverty. (Austria)
8	Raus aus Öl unf gas - Phase-out of oil and gas. (Austria)
9	Tirol 2050 Energieautonom – Tyrol 2050 Energy Autonomy. (Austria)
10	Real Estate tax (IBI) bonus for household owners with renewable energy. (Spain)
11	Cooperative Energía Bonita. (Spain)
12	Som Energia Cooperative. (Spain)
13	Sun4All project. (EU)
14	Viure de l'Aire. Collective wind turbine. (Spain)
15	Good-Move: Regional mobility plan for the Brussels-Capital Region. (Belgium)
16	Low emission Zone in Brussels. (Belgium)
17	CCAM: Electric autonomous and connected mobility network. (EU)
18	Blue and green infrastructure for sustainable cities. (Finland)
19	Coopernico. (Portugal)
20	Fair Energy Transition for All (FETA). (EU)
21	RES development in Dubiecko, Krzywcza and Bircza municipalities. (Poland)
22	Coal Subsidies. (Poland)
23	Smog Alert. (Poland)
24	Clean Air Programme. (Poland)
25	My Electricity. (Poland)
26	Renewable Energy District: Bologna Pilastro-Roveri. (Italy)
27	ManzaEnergía: Energy community. (Spain)

4 Results and Discussions

Out of the 27 past and present initiatives that were analysed 25 were from Europe, 1 from Australia and 1 from Canada. Analysed initiatives can be classified into 7 broad, yet distinct categories.

4.1 Renewable and Heating System Substitution Subsidies

Subsidy funding-based initiatives (e.g., *Energieplan Innsbruck, Raus aus Öl unf gas - Phase-out of oil and gas, RES development in Dubiecko, Krzywcza and Bircza municipalities)* in this category aim to enhance energy transition by promoting the substitution of old heating systems, implementing renewable energy self-consumption installations, and improving energy efficiency in buildings, with positive impacts on decarbonizing households and contributing to green energy production. It is also argued that large scale implementation of these measures is required for prices of necessary resources to drop, as, for instance, PV installation price evolution shows.

Undesired Impacts: Initiatives for renovation and renewable installations often exclude vulnerable citizens, particularly low-income renters, leading to increased rental prices as these are only accessible to citizens with medium to high purchasing power, and usually only attainable by homeowners.

Vulnerability Factors: In renewable energy initiatives they are linked to household ownership and education level, making it difficult for those who rent or have lower education to access subsidies. Some policymakers have introduced complementary initiatives to address the unequal access to subsidies, such as funding-based initiatives like coal subsidies (initiative no. 22).

4.2 Tax Discounts if Renewables Are Installed

Bonification-based initiatives (e.g., *Real Estate tax (IBI) bonus for household owners with renewable energy*) are usually designed to promote renewable energy installations or car renovations. They offer a discount on a particular related tax for the households that install renewables.

Undesired Impacts: These initiatives may worsen socio-economic inequalities by directing public resources towards households or citizens with higher purchasing power, reducing their tax burden and contradicting wealth redistribution efforts, potentially exacerbating the issue of inequality.

Vulnerability Factors: For this kind of initiatives, it is often linked to housing ownership, which is associated with socio-economic conditions. A measure that can be taken to extend the benefits of the energy transition to vulnerable population could be the creation of a renewable energy community.

4.3 Coal Phase-Out

This kind of initiatives (e.g., *A just and fair transition for Canadian coal power workers and communities, Latrobe Valley Authority - manage the just transition associated with the closure of the Hazelwood coal fired power plant, Germany's hard coal mining phase-out*) are often designed to phase out or completely close production of coal from coal mining areas or energy from coal powered power plants.

Undesired Impacts: Coal phase-out initiatives can lead to inequalities and negative impacts on local communities and workers due to job losses, as well as a potential decline in economic activity in affected areas. Some initiatives aim to support affected groups through workshops and training, but often they focus only on qualified employees, neglecting especially women in menial jobs such as cleaning, maintenance etc. In some cases, if in the short-term coal import from abroad continues, these initiatives do not even tackle climate change impacts.

Vulnerability Factors: The closure of a coal powered plant or coal mining not only affects qualified workers, but also the entire local community, including people associated with secondary jobs, women, and indigenous communities, making them vulnerable to the transition process.

4.4 Renewable Energy Projects on Land

Renewable energy production-based initiatives (e.g., *Viure de l'Aire. Collective wind turbine, Coopernico*) are often implemented in rural areas due to the availability of land, and local participation plays a significant role in their acceptance or rejection. The impact of renewable energy projects on different social groups can vary, with some initiatives being seen as good practices while others face rejection due to lack of citizen participation and negative impacts. The choice of technology, such as wind turbines or solar PV plants, can also affect land use and cohabitation with other activities.

Undesired Impacts: If large renewable energy projects are installed in areas that are already oversaturated with other uses of the land, such as agriculture or urban development, t the availability of land becomes an area of conflict and can lead to an increase in the price of the land. This increase in land price makes it difficult for other industries or communities to access the land. Solar PV projects occupying larger areas can impact land use and price more significantly than other types of renewable projects.

Vulnerability Factors: Primarily the vulnerability factor in this case is geographical, meaning it is linked to the physical location of the installation, more so in case of large renewable energy installations. Local citizens who live in the vicinity of the installations are often most impacted for example in the form of noise pollution, visual impacts, changes in local environment, lesser access to and affordability of local land. Often the vulnerability of this group is not related to any personal characteristics or traits.

4.5 Energy Communities

Renewable Energy Communities-based initiatives (e.g., *Cooperative Energía Bonita, Renewable Energy District: Bologna Pilastro-Roveri, ManzaEnergía: Energy community*) aim to include vulnerable groups, such as those in energy poverty, in the energy transition and renewable implementation. All energy communities' initiatives that have explored in this study were all created to address energy poverty and make energy transition accessible to citizens, regardless of socio-economic status. These energy communities actively engage vulnerable groups through collaborative methods and removal of economic barriers, encouraging their participation in the energy transition process.

Undesired Impacts: No significant undesired impact could be identified for this kind of initiatives.

Vulnerability Factors: These initiatives are designed to target individuals or households who are in energy poverty situations, which means they are unable to afford basic energy needs. Low-income households are also included in this category, as they may struggle to pay for energy bills and may not have the resources to invest in renewable energy installations. Structural vulnerable groups are also targeted by these initiatives. This refers to groups of people who are at a disadvantage due to their social or economic status, such as refugees, elderly people, or people with disabilities. The main goal of these initiatives is to provide support to these vulnerable groups and help them access renewable energy solutions that they may not be able to afford on their own.

4.6 Mobility Transition and Air Quality

Air quality in cities is poor due to the high number of vehicles using fossil fuels, leading to local and global pollution. Some cities have implemented measures like banning pollutant vehicles and imposing tolls to improve air quality in the form of low emission zones, entrance tolls, or area restrictions. Approaches are often utilized in this kind of initiatives (e.g., *Citizens' Jury on carbon neutral road transport, Good-Move: Regional mobility plan for the Brussels-Capital Region, Low emission Zone in Brussels*) are penalizing pollutant vehicle owners, incentivizing greener vehicles, and promoting public transport options, which is more beneficial for citizens with fewer mobility options and lower socio-economic status.

Undesired Impacts: Pollution tolls, extra taxes, and pollutant vehicle bans disproportionately affect low-income citizens, the elderly, and those in poorly connected areas, limiting their mobility options. Those who depend on their old pollutant vehicle due to not having enough purchasing power to substitute the vehicle become disproportionately affected. However, improving public transport and incentivizing vehicle substitution can be a more favourable approach to reach vulnerable groups, although certain populations like the elderly and low-income households may still face challenges in accessing alternative transportation options.

Vulnerability Factors: In mobility transition initiatives, low-income households, elderly people, and citizens of poorly connected areas are identified as vulnerable groups.

Approaching these vulnerable groups to understand their needs and identifying incentives for transition towards greener mobility are preferred by vulnerable groups, over bans and penalties.

4.7 Compensatory and Inclusive Measures

This group of initiatives are created and designed with the main objective to compensate or palliate negative impacts inflicted by energy transition policies and initiatives. Initiatives such as *Fair Energy Transition for All and Just Transition Mechanisms* aim to address the negative impacts of energy transition policies by understanding the needs of vulnerable groups and designing mechanisms for a more just transition. Examples like *Latrobe Valley Authority* and *A just and fair transition for Canadian coal power* are initiatives that compensate for the negative effects of coal power plant closures. The initiative *Together against energy poverty in Tyrol* focuses on providing information-based workshops to vulnerable citizens impacted by energy transition plans, while *Coal Subsidies* and *ManzaEnergia* provide economic discounts and access to renewable energy for citizens affected by energy transition initiatives.

Undesired Impacts: If all affected groups are not identified properly, measures might end up addressing needs and concerns of only the more 'visible' groups.

Vulnerability Factors: Usually low-income households, tenants, energy poverty risk situations, and any other particular group negatively affected by other energy and mobility transition initiatives.

In terms of identifying and engaging vulnerable groups, analysis shows that while eighteen of the analysed initiatives identified vulnerable groups, only eleven of them intended or tried to involve or engage in some way identified vulnerable groups in the initiative. Moreover, nine initiatives (i.e., 33% of all analysed initiatives, initiative no. 6, 8, 10, 14, 16, 21, 23, 24, 25) did not identify any vulnerable groups that may be impacted by the initiative.

Rest of the initiatives were categorized and ranked as per their level of vulnerable group engagement (see Fig. 1) taking inspiration from *Sherry Arnstein's participation ladder* (Arnstein, 1969). Among the initiatives that identified vulnerable groups, five initiatives (initiative no. 5, 11, 15, 17, 19) form the base of the participation ladder, meaning they identified vulnerable groups, but did not engage them in the initiative. *Energía Bonita (*initiative no. 11*)* is a relatively new energy community which is trying to remove economic entry barriers for vulnerable groups, but a participation of vulnerable groups does not take place yet. Initiatives like *Good Move (*initiative no. 15*)* has carried out workshops and talks involving general population, but they did not to reach and engage vulnerable groups in the initiative.

Next up in the engagement ladder, there is one initiative among all analysed initiatives that do not engage vulnerable groups to participate directly, but in an indirect way they encourage their participation. The *SomEnergia cooperative* (initiative no. 20) indirectly involves vulnerable groups by organizing contests on energy transition innovation and energy poverty related projects that aim to promote local actions on energy poverty and energy transition fields, to push and incentivise energy transition projects that can be accessible to everyone, including their identified vulnerable groups. This cooperative has created a mechanism, the solidarity cent, in which the cooperative's customers pay one cent voluntarily for each kilowatt-hour consumed to finance support for projects designed to combat energy poverty.

Next group of initiatives employed economic incentives, subsidies and bonifications to help vulnerable groups palliate negative effects of energy transition policies or energy crisis and energy poverty situations. For example, *coal subsidies* (initiative no. 22) is providing economic subsidies to affected vulnerable groups, thereby helping them palliate the rising costs of fuels for their heating systems. *Sun4All* (initiative no. 13) provides discounts on energy bills to the vulnerable groups that participate in the project, who are usually at risk of energy poverty.

One step up in the participation ladder are the initiatives that informs vulnerable groups and provides them with knowledge about energy transition, energy efficiency, energy rights and energy poverty among other related aspects. This empowers vulnerable groups and makes sure that they feel to be part of the energy transition process. *Together against energy poverty in Tyrol* (initiative no. 7) and *Tirol 2050 energy autonomy* (initiative no. 9) are two good examples of this approach where they focus on young generation as fundamental vulnerable group. Transition towards low-carbon energy sources often involves significant economic and institutional reconfigurations, which can disproportionately affect young people who may have limited financial resources and less established positions in the workforce. Additionally, the threat of climate change and the need for a low-carbon economy place a burden on future generations to address these challenges, potentially impacting their quality of life and opportunities for development. Another initiative, *Sun4All* (initiative no. 13), apart from providing energy bill discounts, also informs vulnerable groups about self-consumption of energy or energy efficiency. Another initiative of this group is *Blue and Green Infrastructure for sustainable cities* (initiative no. 18), which not only provides vulnerable groups with knowledge, but also trains them on the topic.

The second highest level in the participation ladder is occupied by the initiatives that organize focus groups, forums and workshops to identify vulnerable groups' needs with regards to the initiative. For example, *Latrobe Valley Authority* (initiative no. 3), *Fair Energy Transition for all* (initiative no. 20) and *A just and fair transition for Canadian coal power workers and communities* (initiative no. 1), use bottom-up approaches to allow vulnerable groups to express their needs so that the initiative is designed following their opinions and concerns. *Citizens' Jury on carbon neutral road transport* (initiative no. 2) employs a similar approach, but through an aleatory selection process and statistical study involving vulnerable groups. Similarly, *Germany's hard coal mining phase-out* (initiative no. 4), uses such an approach, but in this case, through mining workers union as representatives of the vulnerable group.

Finally, the highest level of participation and engagement of vulnerable groups is achieved by initiatives where vulnerable groups are allowed to participate and directly be part of the decision-making of the initiative. For example, *Pilastro-Roveri energy community* (initiative no. 26) and *ManzaEnergía energy community* (initiative no. 27) allow their members from vulnerable groups to freely participate in their meetings and decision-making processes by employing collaboration/cooperation and governance mechanisms with active and encouraged engagement levels. It is worth noting that both of them are energy communities, and that they are designed to directly approach and involve vulnerable groups.

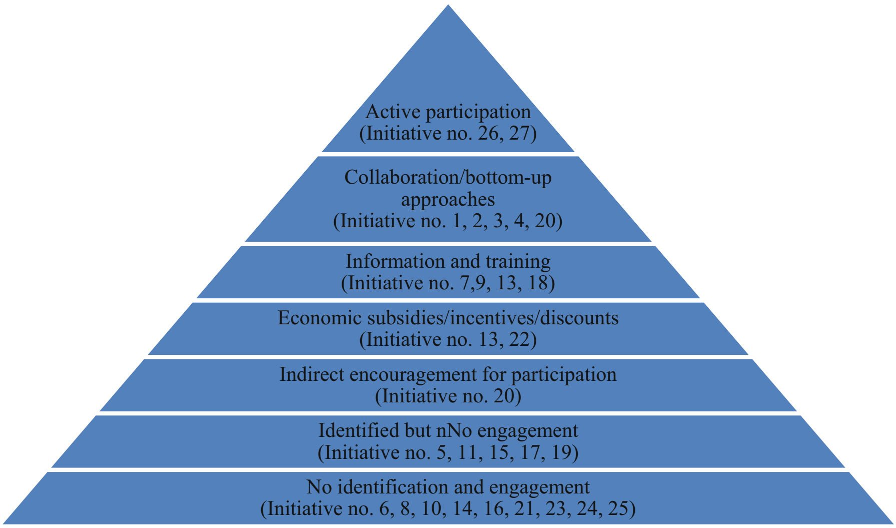

Fig. 1. Levels of engagement of vulnerable groups in analysed initiatives

5 Conclusion

The world is currently encountering significant sustainability challenges, including but not limited to climate change, energy insecurity, biodiversity loss, and social inequalities. In order to tackle these challenges, it is imperative to implement exnovations that can take us to a low-carbon regime by substantially modifying energy and mobility systems. Nevertheless, this transition should not come at the cost of inconvenience and imposed suffering of vulnerable groups. Our analysis showed that there is a lack of understanding, awareness or recognition among policy and decision makers when it comes to vulnerability factors and undesired impacts associated with transition policies and initiatives. One-third of the analysed initiatives did not even identify any vulnerable groups and only less than half of the initiatives undertook some effort to engage citizens or account for concerns of vulnerable groups, while only two (out of 27 initiatives analysed) allowed vulnerable groups to take part in the decision-making process. This lack of analysis of inequalities and vulnerabilities prior to implementing low-carbon transition initiatives and policies can not only lead to lower acceptability of these initiatives, but also can cause serious negative consequences, such as deepening inequalities and increasing energy and mobility poverty of certain societal groups. Effective addressal of issues related to fairness and justice are imperative for successful implementation of transition policies. For a diverse society such as in Europe and all across the world, most of the energy and mobility transition policies are likely to involve questions of distributive and procedural justice, along with other ones such as recognition, intergenerational and intersectional justice. Given that changes in energy and mobility systems have wide-ranging socio-economic and socio-ecological consequences, failure to consider justice-related impacts could result in more vulnerable groups being further endangered and marginalized.

Therefore, it is recommended that design and implementation of transition initiatives and policies in the energy and mobility sector must include specific studies on social inequalities, and potential undesired impacts and compensatory measures, considering the entire community that is going to get affected by the initiative or policy. It is advised to include representatives of different social groups in the design and monitoring of energy transition initiatives and to reduce, if not eliminate entry barriers for vulnerable groups. Public participation and inclusion are vital for a just and democratic transition process. Collaboration between public authorities (e.g., departments of energy and social services), local NGOs, private companies and representatives from vulnerable groups is recommended. The process of transitioning towards a more just society involves making trade-offs regarding the distribution of benefits and costs between environmental and social objectives, as well as managing conflicts related to distributional, procedural, recognitional, cosmopolitan and restorative justice. To effectively address the multifaceted impacts of this transition, it is imperative to ensure policy coherence and coordination across sectors and regions. Furthermore, it is crucial to better articulate the intergenerational justice and long-term benefits associated with these transition policies. These are also essential to consider for a successful implementation of the Just Transition Fund (JTF) and the associated Territorial Just Transition Plans across Europe.

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Application of ENROAD Tool for Pre-feasibility Evaluation of Renewable Energy Projects Within the Road Environment

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Abstract. Roads are vital infrastructures for the mobility of people, transport of goods and, in general, for every country's economic development. On the other hand, roads have a significant impact on the environment throughout their life cycle. Thus, GHG emissions from the transport sector in the EU have substantially grown in the last few years, unlike other sectors like energy or manufacturing industries, which managed to greatly reduce their GHG emissions.

Several solutions are currently in place to minimize the environmental impact of roads, such as the use of more sustainable materials, the use of biofuels by vehicles, the promotion of cycling and public transport, or the electrification of roads. The use of renewable energies, such as solar and wind energy, should also be considered to power road infrastructures and services such as lighting, signaling or even electric vehicle charging stations.

A case study is presented here for application with ENROAD, a web-based, open source, road-focused tool for decision making at a very early stage of investments in renewable energy projects. The solution provided shows the potential use of a specific site to cover the energy needs of a road infrastructure, also allowing the comparison between different generation alternatives.

Keywords: Roads · Emissions · GIS · Renewable energy · Solar · Wind

1 Introduction

It is very well known that road infrastructures are crucial for the social and economic prosperity of countries and citizens. Road networks not only ensure access to key public services, such as education and health, thereby contributing to people's quality of life, but their expansion has the potential to increase countries' GDP and employment rates.

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Hence, there is a need to build roads to help connect people and goods. On the other hand, investment in transport infrastructure represents: a considerable share of countries' GDP, a larger share of public investment, and a significant environmental impact associated with its entire life cycle.

In the last three decades, GHG emissions from the transport sector in the EU have grown by more than 30%, in contrast to other sectors that managed to reduce them considerably [2, 3]. The European Climate Law sets the goal of a climate-neutral EU by 2050 and sets a net reduction of GHG emissions of at least 55% compared to 1990 by 2030 [4]. Likewise, the European Green Deal [5] claims that a 90% reduction in GHG emissions from transport is required by 2050 to achieve that climate neutrality.

Considering that in 2020 the share of energy from renewable sources in the EU transport was only 10.2%, mainly due to the increased use of biofuels in Europe over the last years [6], it seems that there is still a long way to go for renewables to make a significant contribution to mitigating the environmental impact of roads.

In the context of this situation, the ENROAD project, funded by different National Road Administrations in the framework of the CEDR (Conference of European Road Directors) Research Call 2019 [7], aims to provide a pre-feasibility evaluation tool for renewable energy projects within the road asset with a technical, financial and environmental approach.

2 The ENROAD GIS-Based Tool: Framework and Particularities

General outcomes of the ENROAD project have been: the assessment and modelling of renewable solutions for potential implementation alongside the road asset; practical explanation of legislative framework across the evaluated countries regarding the generation and distribution of RE; definition of effective business model and cases for economic and financial assessment based on the technology and facility individually considered; and finally, the development of an easy-to-use tool aimed at providing a preliminary assessment NRAs assets' potential for the renewable power generation.

To comply with this pre-feasibility evaluation, the GIS tool has been designed to provide: an estimation of power and potential energy generation in a specific site; a financial pre-feasibility study of the renewable energy installation; a preliminary environmental assessment mainly associated with the core technology. It should be noted that this tool is intended to help NRAs in their decision-making process, but in no case can it be taken as a design software nor can it be used as a substitute for the professional advice that is mandatory when dealing with this type of project investments.

The solutions provided by the ENROAD tool are all based on the potential location of the energy technology that is planned to be installed. For this reason, a GIS system is needed to run behind the tool that is able to deal with the information contained in the different geodatabases used, most importantly the energy databases. End users can upload their own geodatabases, such as parcels, grid connection points, etc., to add precision in finding the most suitable location.

The ENROAD tool is built up of two elements: (1) the GIS-based tool itself, a web service that makes use of certain input data and allows the user to select site and area for different energy technologies, and estimates the total capacity (number of units, MW) of the new renewable energy installation; (2) a Microsoft Excel template that has to be uploaded into the tool, where inputs and outcomes such as the annual energy generation (kWh) or the whole package of financial and environmental indicators, are displayed in the form of a complete study case for the area selected. The user decides the amount and complexity of input data that is introduced: from basic location, area, available financing or starting year of investment to the more specific energy demand for storage, inflation rate or OPEX standards.

In order to facilitate upgrading and maintenance to a certain extent, users with certain knowledge and access to technical data can modify the parameters of each of the 6 technologies initially incorporated into the tool (two small wind turbines, two large wind turbines and two types of PV panel), and even replace each of the technologies.

3 Application of the ENROAD Tool to a Case Study

As part of the ENROAD project, three study -business- cases were carried out using the ENROAD GIS-based tool, one of which was a charging station for EVs (customer-side or demand model) in Germany. The roll-out strategy was to offer a series of charging stations with specific agreements for parcel and logistics companies. In other words, the NRA (or a company on its behalf) builds a charging station in plots located next to the highway network, close to companies that can make use of those charging points at night schedule, with the installation including batteries for such schedule.

For the selection of the site, three requirements had to be met: (1) a good productivity in terms of primary energy; (2) an adequate level of traffic to help maintain a good level of use of the facilities to achieve the level of profitability; and, (3) the plot, which was assumed to be owned by the NRA, would increase in value with the new use. In this context, the ENROAD tool was used to find the area to place the renewable energy facility for energy generation, define the number of panels and turbines that can be displayed in that area, calculate the energy generated and provide a preliminary financial end environmental assessment.

For the simulation, users are encouraged to enter updated values of financial inputs such as the forward prices or the annual interest rates in the template. With regards to the charging prices at stations in Germany, 490.00 €/MWh seemed a feasible price on the basis of own market tracking, while the market price of the electricity considered was 122.71 €/MWh[1].

With both wind and solar PV primary energy in mind (the ENROAD tool provides the user the site's wind and PV power potential), and with the information gathered in the BAST website [8], the connection between the A6 Ludwigshafen-Nord 23 and the B9 highway (Mannheim, Frankfurt) was selected as a good site to install solar PV panels, due to the impracticability of using large wind on this spot (small wind was previously discarded). Three available parcels were therefore selected and their areas were entered

[1] Energy spot price in Germany in october 11th 2023.

into the ENROAD tool. Figure 2 shows site, number and arrangement of one of the types of Monocrystalline PV panels, as calculated by the ENROAD tool for those areas (Fig. 1).

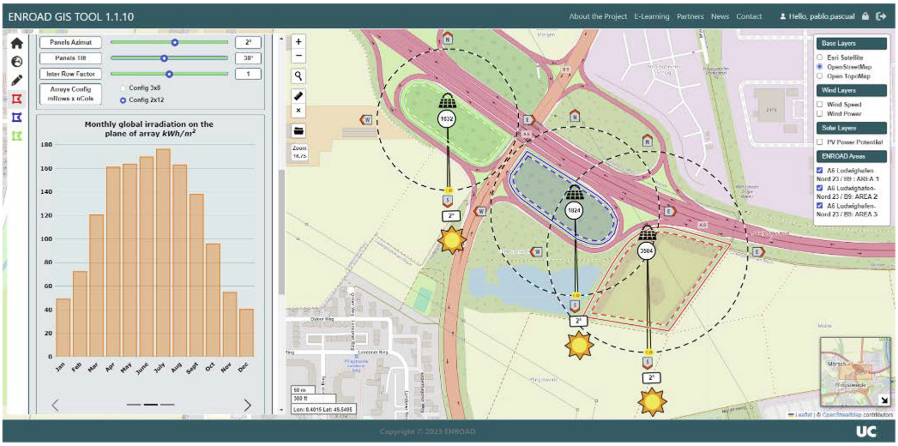

Fig. 1. Arrangement of solar PV panels in the parcels selected (ENROAD). Source: Authors

Table 1 shows the number of elements calculated by ENROAD for each previously defined parcel and the six eligible renewable energy technologies. The surface areas (m2) of these plots are also shown.

Table 1. Units of RETs as calculated by ENROAD for the selected areas

Area	m^2	SW1	SW2	LW1	LW2	PV1	PV2
1	28,577	50	102	1	1	3,504	2,208
2	15,816	29	56	1	1	1,824	1,320
3	13,631	24	49	1	1	1,632	1,080
All	58,024	103	207	3	3	6,960	4,608

SW1: Bornay 6000 (6 kW); SW2: Aeolos-V (3 kW); LW1: Vestas V90 (2 MW); LW2: Vestas V112 (3.3 MW); PV1: JA Solar (330 W, Mono); PV2: JA Solar (530 W, Mono).

Having decided on PV as the most suitable energy source, the charging station was designed to have an initial charging capacity given by 8 charging points connected to 6,960 modules with 330 W maximum power or 4,608 modules with 530 W maximum power. On the other hand, if electric charging of high-end vehicles is considered, each of those charging points should be able to supply 250 kWp. In that case, the total peak power required for the two potential arrangements (2,000 kWp) would be lower than the 2,296 kWp and 2,442 kWp available.

In terms of the energy production in the area selected, the ENROAD tool estimates yearly values of 2,418,727 kWh and 2,570,891 kWh for the two technologies. Based on the standard of one hour of recharge point occupancy per vehicle, a total of 9,675 and 10,283 operations per year would be possible, i.e. 26 and 28 operations per day, and annual energy demands of 2,372,500 kWh and 2,555,000 kWh would be required. With an energy price of 0.490 €/kWh, revenues would amount to 1,185,176 € and 1,259,736 €, respectively.

As a first and fast approach to the capacity and performance of the PV system, the ENROAD tool generates a financial dashboard with four key performance indicators (KPIs) for the recommended renewable energy technology (Fig. 2), which in this case turned out to be Monocrystalline JA Solar 330W (the use of wind turbines was technically discarded for their proximity to the highway). This dashboard explains the effect of the RET's yearly efficiency losses; the inflation rate (Harmonized Index of Consumer Prices); the debt interests; and the financial market interest rate for financial discounts, over the installation operative life, comparing the cost of the starting year with the Levelized Cost of the Energy (LCOE) effectively produced.

Energy average price 2024-2044	Recommended RET
490.00	**Monocrystalline JAM60S10-330/PR**
EUR/MWh	-
First Year Total Cost (FYTC)	COST GAP (LCOE - FYTC)
41.14	**56.88**
EUR/MWh	EUR/MWh
LCOE for selected RET (LCOE)	COST GAP (LCOE - FYTC)/ FYTC
98.02	**138%**
EUR/MWh	-

Fig. 2. LCOE Dashboard generated by the ENROAD tool. Source: Authors

In addition to the dashboard, a selection of financial indicators for the 6 technologies in the ENROAD tool are presented in the Summary sheet of the template that includes starting total investment, Net Present Value, Internal Return Rate, Accrual Accounting Return Rate, sales for break-even point and CO2 emissions savings. In Fig. 3, the values of these indicators only for the PV technologies are shown. The solar PV systems seems to generate good financial returns as a starting point for the elaboration of a business plan with own CAPEX and OPEX for the EV charging station.

If instead of a price of 490.00 €/MWh, a reference market price of 122.71 €/MWh is adopted to simulate the sale of energy to the grid (supply-side model), more moderate results would be obtained, but still adequate for the financial investment (Fig. 4).

RESULTS FOR THE DIFFERENT TECHNOLOGIES		Tech_5 Monocrystalline JAM60S10-330/PR	Tech_6 Monocrystalline JAM72S30-530/MR
Payback period	Years	3	3
NPV	EUR	16,772,212	18,830,669
IRR	%	35.76%	44.38%
AARR	%	112.06%	136.93%
Sales for Break-even Point Based on First Year Production	EUR YR	99,513.88	90,127.29
CO2 Emissions Savings	Tonne CO2/kWh year	952	1,012

Fig. 3. Some of the financial indicators delivered by the ENROAD tool. Source: Authors

RESULTS FOR THE DIFFERENT TECHNOLOGIES		Tech_5 Monocrystalline JAM60S10-330/PR	Tech_6 Monocrystalline JAM72S30-530/MR
NPV	EUR	96,716	1,106,103
IRR	%	3.34%	6.34%
AARR	%	20.96%	26.84%

Fig. 4. Financial indicators delivered by ENROAD for a supply-side model. Source: Authors

4 Conclusions

The solution provided by the ENROAD tool to this case study confirms its validity to provide a very first approximation to the capacity of renewable energy technologies to generate energy in a selected area.

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Exploration and Synchronization of Greening of Shipping by Means of Retrofit: The SYNERGETICS Perspective

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Abstract. The "greening" of shipping remains a challenge despite the development of technologies aiming at decarbonisation and reduction of air-pollutant emissions. Considering a wide variety of ship types and applications, the choice of the most adequate greening solution for a ship of certain size, type, and operational profile is not straightforward. SYNERGETICS is a Horizon Europe Innovation Action which aims at supporting the greening of inland and coastal shipping by addressing the potentials of retrofit technologies. This paper presents first findings of SYNERGETICS which aim at establishing the synergies between the knowledge available from previous and ongoing research ("Exploration") and the experiences gained from past and ongoing pilot projects ("Synchronization"). A comprehensive database of pilot projects containing 115 inland vessels and 50 coastal ships was created and analysed to establish and explain the trends in greening of inland and coastal shipping. It was found that most of the pilots in inland navigation are conducted on vessels with relatively low power demands and/or with low variations of operational profiles, while coastal shipping features a relatively low number of pilots. This increases the certainty for shipowners but limits the possibilities for scaling up the greening of shipping.

Keywords: inland vessels · coastal ships · retrofit · decarbonization · air pollutants reduction · SYNERGETICS

1 Introduction

SYNERGETICS (Synergies for green transformation of inland and coastal shipping) is a Horizon Europe Innovation Action in support of the greening of inland and coastal shipping by addressing the potential of retrofit technologies. In context of SYNERGETICS, the "greening" implies the application of innovative technical (design) measures on ships in efforts to achieve decarbonisation and reduce the emissions of air pollutants. In view of uncertainties related to the impact of the innovations on the ship operation

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and/or the absence of adequate regulatory framework, such measures are realized in "pilots" – the vessels which provide insights into operational aspects and potentials for scaling up of the solutions to the fleets.

Establishing synergies with past and ongoing greening pilots as a means of learning from practical experiences gained in their deployment and operation is carried out within "Synchronization", one of the activities performed in the first phases of SYNERGETICS. To facilitate synergizing with the pilots, a comprehensive Pilot database was created with information on 115 inland and 50 coastal shipping pilots performed in period 2008–2026. Using the information from the Pilot database, it is possible to establish trends in greening of ships, such as the technologies most commonly used depending on the ship type, the evolution of the greening efforts considering the time of the pilot deployment, etc.

The observed trends may be driven by a range of factors (e.g., maturity and feasibility of the technologies, policy incentives and supportive financial instruments, development of the necessary infrastructure, etc.). The knowledge which could explain the identified tendencies is fragmented and dispersed over numerous research projects. Harvesting and integration of such knowledge is performed within "Exploration", a SYNERGETICS activity which runs in parallel with "Synchronization".

2 Synchronization: Identification of Trends in Greening of Ships

An entry to the SYNERGETICS Pilot database contains information on the project (project name and coordinator, funding program, location, start and end date of the project), the pilot itself (location, starting date and duration) including the technical specifications (type of vessel, type of innovation applied, type of alternative energy system, onboard storage and bunkering method), etc.

Table 1. Types of inland vessels and coastal ships represented in the Pilot database.

Inland vessels		Ferries	19%
Motor vessels ($L < 80$ m)	6%	Large cabin vessels	1%
Motor vessels dry cargo (80m $\leq L < 109$ m)	7%	Coupled convoys	2%
Motor vessels liquid cargo (80 m $\leq L < 109$ m)	1%	Push boats ($P < 500$ kW)	3%
Motor vessels dry cargo ($L \geq 110$ m)	9%	Push boats ($500 \leq P < 2000$ kW)	3%
Motor vessels liquid cargo ($L \geq 110$ m)	10%	Push boats ($P \geq 2000$ kW)	2%
Day trip and small cabin vessels	37%	Workboats	1%

Coastal ships		Cruise ships	2%
Tugboats	14%	Fishing vessels	4%
Offshore supply vessels	18%	Dredgers	4%
Ferries	26%	Pilot boats	2%
Cargo ships	28%	Workboats	2%

The Pilot database comprises both the pilots implemented by retrofitting existing ships and the pilots realized on newbuilt vessels. Newbuilds make 63% of pilots on inland vessels; as for coastal ships, the share of newbuilt pilots is lower, but still high (54%). The database includes all major types of inland vessels and coastal ships (see Table 1). (In context of SYNERGETICS, "coastal ships" are seagoing ships which operate in ports, along coastlines, between islands and in marginal seas.) Most of the pilots in inland waterway transport (IWT) are implemented on small passenger ships ("day trip and small cabin vessels") and ferries (37% and 19% respectively), while the least number of pilots is conducted on push boats (8% considering all push boat categories). Cargo ships (28%) and ferries (26%) dominate the coastal pilots.

Three types of innovations are reported in the database: electrification of the main propulsion plant, use of alternative fuels, and energy-efficiency measures. The identified alternative energy systems comprise hydrogen in fuel cells (H_2-FC) and in internal combustion engines (H_2-ICE), methanol in fuel cells (CH_3OH-FC) and in internal combustion engines (CH_3OH-ICE), liquefied natural gas (LNG), compressed natural gas (CNG), and ammonia in fuel cells (NH_3-FC) and in internal combustion engines (NH_3-ICE). Energy-efficiency measures include design interventions (other than electrification or utilization of alternative fuels) leading to decreased fuel consumption, primarily the hydrodynamic improvements of propulsor and/or hull.

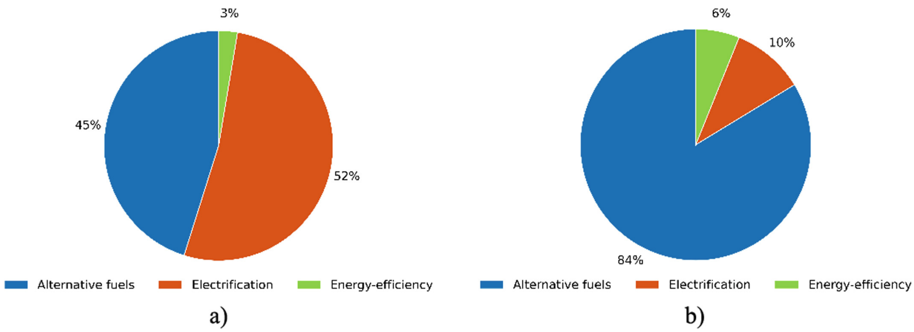

Fig. 1. Innovative technologies used in greening pilots on a) inland vessels and b) coastal ships.

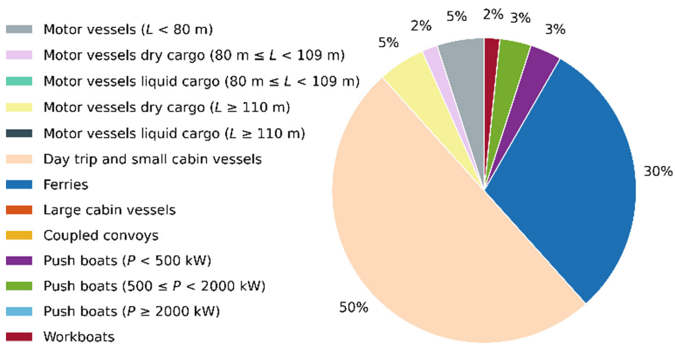

Fig. 2. Electrification pilots on inland vessels; breakdown by ship type.

Regarding the choice of innovative technology used (Fig. 1), electrification and alternative fuels are almost equally represented in greening of inland vessels (52% vs.

45%). In case of coastal ships, however, electrification comprises just 10% of pilots (five ships, three out of which are ferries) while alternative fuels are being implemented in as much as 84% of pilots. Energy-efficiency measures appear to be seldom used (2% in inland vessels pilots and 6% in coastal ships pilots). In inland navigation, electrification is mostly used on day trip and small cabin vessels and ferries (50% and 30% respectively), see Fig. 2.

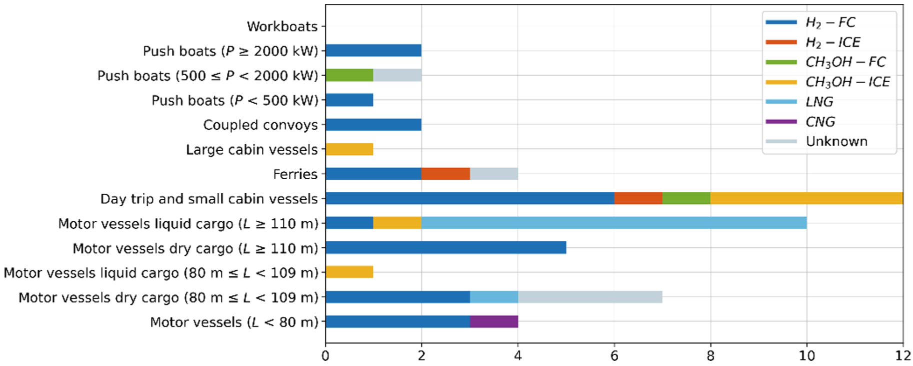

Fig. 3. Alternative fuels pilots on inland vessels.

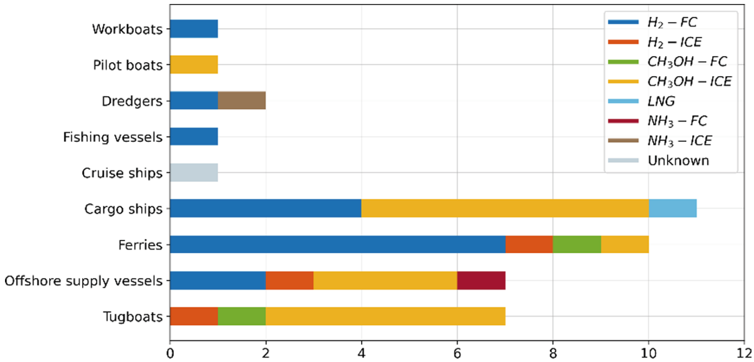

Fig. 4. Alternative fuels pilots on coastal ships.

The utilization of alternative fuels is more equally spread across the types of inland vessels, Fig. 3. In fact, self-propelled dry and liquid cargo vessels with $L > 80$ m comprise some 45% of the alternative fuel pilots. The most prominent types of alternative energy systems used in inland navigation pilots are H_2-FC, i.e., almost half of the pilots (49%), followed by LNG (17%)[1] and CH_3OH-ICE (14%). In coastal shipping, CH_3OH-ICE and H_2-FC have equally prominent roles (both 40%); the principal alternative fuels pilots are the major ship types (tugboats, offshore supply vessels, ferries, and cargo ships), Fig. 4.

[1] LNG pilots comprise early applications and/or applications with a specific learning potential, not all inland and coastal ships powered by LNG.

Another prominent feature of coastal pilots is the use of NH_3 (which, so far, found no pilot application in IWT), albeit in two pilots only.

3 Exploration: Analysis of the Observed Trends

Even though the pilots were carried out on all major ship types used in IWT and coastal shipping, the diversification seems to be relatively limited when it comes to inland vessels. The pilots are mostly performed on small passenger ships and (usually small) ferries (see Table 1), that is, on vessels with relatively low power demands, operating in comparatively controlled environments, with low variations in day-to-day operational profiles. Since such ships carry people (i.e., light "cargo") the options for modification of standard designs and mitigation of novel risks (inherent to some of the greening solutions) are greater. Furthermore, such vessels travel over short distances, staying close to the "home port" where they can be readily taken care of in case of technical issues with the novel technologies. These factors limit the risks and diminish the costs associated with the application of innovative technologies. Moreover, a greener passenger vessel may appeal better to the public and, possibly, attract more customers. However, the available data (see [1]) indicate that day trip vessels and in specific, ferries, are not the major emitters in inland navigation. Less than 20% of pilots is performed on large self-propelled liquid and dry cargo ships ($L \geq 110$ m) which are among the greatest emitters in IWT. The total of eight pilots performed on push boats across all power ranges is a consequence of high power demands and constrained space, as push boats are essentially floating engine rooms.

The diversification with respect to ship types used as pilots is greater in coastal shipping (see also Table 1). However, the number of pilots is much lower than in inland navigation despite the rapid growth of the coastal shipping in the period covered by the Pilot database (see [2]). Depending on the size, type, and operational area, coastal ships may be exempt from several international and European environmental regulations (such as EU Emission Trading System and FuelEU Maritime) which is – in combination with high investment costs – disincentivizing the greening efforts.

The low share of electrification pilots on coastal ships (see Fig. 1) is a consequence of the requirements for greater autonomies and/or higher deadweight-to-lightship ratios, which translate to greater power demands and limited space and weight available for batteries. On the other hand, higher share of electricity-based pilots in inland shipping may be explained by the fact that most of them are conducted on small, short-distance passenger ships (Fig. 2) which allow more frequent charging and offer more space and weight for storage of batteries. Measures aimed at reduction of fuel consumption are often implemented as a part of the regular business plans, rather than distinct projects, which may explain the low number of energy-efficiency pilots (Fig. 1). Additionally, as fuel costs are often covered by cargo owners, not by vessel owners / operators, the latter may not be incentivized to invest in energy-efficiency measures unless this would give them a clear competitive advantage in the market.

Numerous hydrogen pilots both in inland and coastal shipping (see Figs. 3 and 4) may be partly explained by the adoption of a number of national and transnational hydrogen roadmaps and related financial instruments which bolstered the hydrogen applications across industries, including shipping. Many policy makers regarded IWT and coastal shipping as sectors which could boost the demand for hydrogen (see [3]), which led to hydrogen-related programmes being placed high in subsidy schemes.

4 Conclusions

The paper presents the first findings of the Horizon Europe Innovation Action SYNERGETICS. Initial phases of SYNERGETICS integrate the knowledge from past and ongoing research projects (Exploration) with the experience gained from past and ongoing pilots (Synchronisation) to facilitate the green transition of inland and coastal fleets. A comprehensive database of pilot projects was created which enabled the identification of the trends in greening of inland and coastal ships. To the best of the authors' knowledge, such a database is unique. It is to be noted that even though the greening of ships is a "hot topic" the relevant information is often scarce.

The analysis of the identified trends showed that the shipowners, being faced with large uncertainties linked to implementation of novel technologies, whilst not being sufficiently incentivized, hesitate to engage in greening beyond the pilot applications at the lower risk end. Most of the pilots in IWT are performed on small vessels, with lower power demands. In coastal shipping, the total number of pilots is low, and the developments started later than in inland navigation. Thus, the replicability of pilots and the possibilities for scaling up of greening from single vessels to fleets is limited.

The potentials of retrofit are still largely untapped, considering that most of the pilots are realized on newbuilds. This is particularly important for inland vessels which have much longer lives than seagoing ships. This gap confirms the importance of SYNERGETICS which focuses on potential of greening of ships by means of retrofit.

The Pilot database does not quantify the level of greening attained, e.g., in terms of achieved emissions reduction. A more elaborate assessment would require more sophisticated data, e.g., the information on production of the alternative fuels and the sources of electricity. Therefore, the database registers greening efforts and identifies main directions but does not aim at assessing the achieved environmental performance. This remains the task for the future work of SYNERGETICS.

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Hydrogen-Powered Rail Maintenance Vehicle: System Design and CO_2 Emissions Reduction

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Abstract. This article presents a design analysis of retrofitting the rail service locomotive vehicle X534 originally used by the Austrian Federal Railways (ÖBB) from a diesel-electric system to a hydrogen-electric hybrid configuration. The conversion aims to address greenhouse gas emissions and achieve zero emissions in workplace environments. The vehicle operates in a stop-and-go mode for short distances and long trips to work sites, posing a challenge for a pure battery system due to range limitations. To overcome this limitation, a specific drive train configuration for the retrofitting has been adopted, comprising a 120 kW fuel cell system, a 70 kWh NMC Li-Battery, and three hydrogen tanks storing approximately 22 kg of hydrogen. A numerical model in Matlab/Simulink/Simscape framework, incorporating the hydrogen fuel cell system, cooling system, auxiliary systems, and the main components of the hybrid powertrain, demonstrates the feasibility and effectiveness of this retrofit. This research contributes to the ongoing efforts to find sustainable alternatives for traditional fossil fuel-based transportation systems. In particular, in the hypothesis of a green hydrogen scenario, a reduction of up to about 49 tons of CO_2 per locomotive per year can be achieved.

Keywords: Retrofitting · CO2 emissions reduction · Hydrogen

1 Introduction

The electrification of railway transport has emerged as a crucial strategy to mitigate greenhouse gas (GHG) emissions and reduce the environmental footprint of mass transportation [1]. European countries have consistently invested in modernizing rail infrastructure. However, a significant portion of the global freight and passenger railway fleets still rely on diesel fuel, necessitating cleaner and potentially carbon-neutral alternatives to lessen the environmental impact of rail transport [2].

Technological solutions have been implemented on diesel-based locomotives to improve air quality, but they have had limited success in reducing GHG emissions. An alternative approach involves fuel replacement, although its effectiveness depends on the nature of the fuel source, presenting challenges, especially for bio-based fuels [3, 4].

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With the growing integration of renewable energy sources and the production of green hydrogen, hydrogen-fueled trains have emerged as a promising solution [5]. These trains offer energy-efficient operation similar to electric rail transport while boasting limited GHG emissions, potentially achieving zero emissions depending on the primary energy source used to produce hydrogen. One significant advantage lies in adopting low-temperature Proton Exchange Membrane (PEM) fuel cell systems, which provide direct energy conversion and substantial reductions in NOx emissions [6].

The retrofitting of fuel cell systems in existing diesel locomotives holds promise due to two key factors:

1. Economic Benefits: Retrofitting can avoid substantial investments in infrastructure, including overhead lines, substations, and primary supply lines. This cost-effectiveness is particularly relevant in locations with legacy infrastructure or challenging terrain, where traditional electrification may be cost-prohibitive.
2. Speed of Implementation: Retrofitting allows the rapid transformation of high-emission locomotives into Zero-Emission Vehicles, addressing a global issue promptly. This approach is highly relevant for work environments where emissions directly affect the health of on-site teams.

PEM fuel cell retrofitting becomes especially attractive in specific applications like construction and rail service vehicles. These vehicles demand zero local emissions due to the proximity of the work environment to the exhaust outlet. While battery solutions are ideal for short-distance, stop-and-go operations, they fall short when work sites are far from depots and weight constraints come into play.

This paper proposes a study on powertrain refurbishment for construction and rail service diesel locomotives, focusing on a PEM fuel cell-based solution. A numerical model of the powertrain, implemented in Matlab/Simulink, supports design activities and real-time operation monitoring. The model encompasses all essential components involved in retrofit operations, including locomotive dynamics, auxiliary systems for the fuel cell supply and cooling, and the pneumatic braking system. The validity of the approach has already been successfully tested in a previous study for a shunting locomotive application [7]. The study evaluates the techno-environmental performance of the hydrogen-powered powertrain and compares it to a battery-based solution, ultimately showcasing the limitations of battery electric vehicle (BEV) retrofitting for such applications.

In summary, this work aims to advance understanding of hydrogen applications in the railway sector, emphasizing their strengths and weaknesses in real-world applications. By doing so, it contributes to the broader goal of reducing GHG emissions while meeting the required performance standards in rail transportation.

2 Methodology (Modelling Approach)

A railway service vehicle is used for internal railway activities such as construction, maintenance, inspections and intervention. In this paper the study of powertrain refurbishing is proposed for a diesel-electric powered motor tower cars and in Table 1 the main technical specifications are listed.

Table 1. Locomotive technical details [8].

Weight	21 [t]
Diesel engine	MAN D2566ME
Continuous Power	122/147 kW
UIC of locomotive	1A
Max speed	80[km/h]

A hydrogen-fuel cell hybrid powertrain consists of several key components: traction motor, DC/DC converter, fuel cell stacks (FCs) and battery packs. Generally, the size of the FCs and the battery packs is chosen in such a way that the former can meet the average power demand for traction, while the latter can handle power peaks and transient phases [9]. In this work we aimed to strike a trade-off between achieving the desired performance and accommodating the spatial limitation of the original locomotive.

2.1 Hybrid Powertrain and Simulink Model

Figure 1 shows the Matlab/Simulink model used to perform simulation and test the locomotive and hydrogen powertrain performance. The electric traction motor is powered by two energy sources: two 35 kWh battery pack, whose rated voltage is 350 V and three 40 kW rated power FCs. Battery packs and FCs are linked in parallel with a DC/DC converter to adapt voltage to the DC-bus.

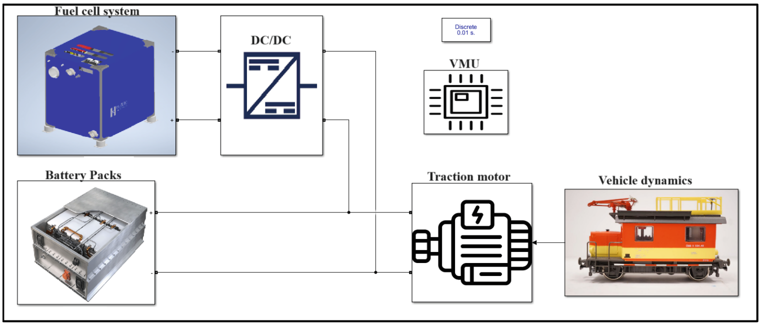

Fig. 1. Simulink railway vehicle model (Source: Authors).

The hybrid powertrain is connected to the "Vehicle Dynamics" block, where longitudinal dynamic of the locomotive is described using the following equation:

$$T(t) - R(t) - B(t) = M \frac{dv(t)}{dt} \quad (1)$$

where T represents the locomotive tractive effort, R is the sum of the motion resistances (aerodynamic drag, rolling resistance, slop/gradient resistance [10]) and B is the braking force. In addition to the main components described above, the Simulink model of the locomotive also implements in detail the fuel cell cooling system and the pneumatic air brake system, thus simulating both the effects of temperature and the power consumption of main auxiliary components such as fans, pumps, and the air compressor. In Fig. 2 a comparison is shown between the specifications provided in FCs datasheet and those obtained from the computational model of fuel cell system. It is evident that the properly calibrated Simulink model is capable of accurately replicating the real performance curves.

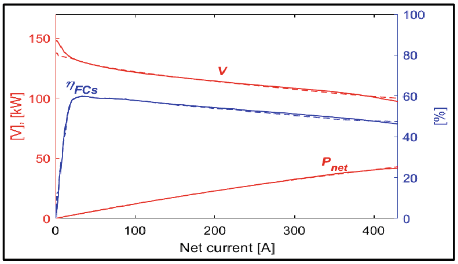

Fig. 2. Fuel cell performance curves: simulated (dashed line) and datasheet (continue line).

3 Results and Discussion

In this section, we will present an analysis of the performance of the hydrogen hybrid powertrain and compare it to that of a fully electric powertrain, with an emphasis on the challenges posed by the latter for the specific application. Furthermore, we will demonstrate the reduction in carbon dioxide (CO2) emissions resulting from the retrofit operation. The duty cycle used in the simulations is shown in Fig. 3. The initial and final segments at 80 km/h represent the distance (approximately 130km) for reaching and returning from the working site. On the other hand, the central segment consists of alternating sections of constant-speed segments up to 10 km/h (for about 60 m) and 20-min stops during which 1 kW of power is required to perform maintenance interventions on the railway line. In hybrid powertrains, the power splitting between different energy sources plays a pivotal role, impacting both performance and efficiency, as well as in safeguarding the useful life of components. In our study, the fuel cell is controlled using a range extender control logic. It activates the fuel cell when the battery SOC drops below 70%, requesting a net current of 25 A until the SOC reaches 80%. Under these conditions, the FCs operates near its maximum efficiency point. If the SOC drops below 60% due to a high demand for traction power and auxiliary systems, the control system increases the current request to 150 A, while maintaining relativity high system efficiency. Figure 4 shows the hydrogen hybrid powertrain energy distribution. It can be observed that all the required energy is supplied by hydrogen, while the net energy provided by the batteries is globally zero.

The on-board hydrogen tanks have a capacity of 22 kg, and about 13kg are used to complete the mission. In a full electric configuration, 8 battery packs are required

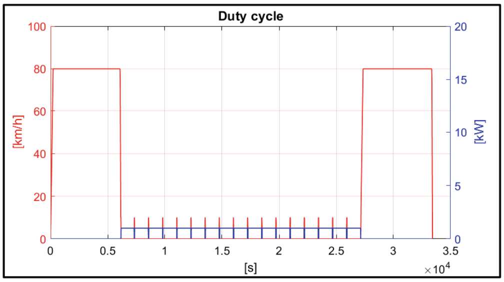

Fig. 3. Typical railway service vehicle duty cycle.

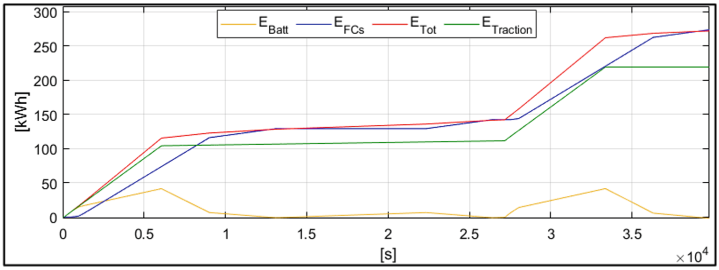

Fig. 4. Hybrid powertrain energy distribution.

to complete the duty cycle with almost no SoC remaining at the end of the mission. However, for this specific retrofitting application, there is a challenge in finding the necessary space without making significant modifications to the railway vehicle. Much of the available space on the locomotive's roof is occupied by the pantograph, which is essential for safety grounding the catenary line during maintenance operations.

Table 2 reports the main results for the two configurations. It can be noted that the hybrid solution, despite its higher energy requirements, provides greater range autonomy and is not dependent on the availability of electricity at the work site for battery charging.

Table 2. Main simulations results

	Hydrogen Hybrid Powertrain	Full electric Powertrain
H2 used [kg]	13	0
Energy required [kWh]	270	221
$SOC_{initial}$ [%]	80	80
SOC_{final} [%]	80	<10
Mission distance [km]	270	270
Estimated range [km]	456	270

Regarding the CO_2 emissions reduction compared to the original diesel locomotive, assuming a diesel engine consumption of 195 g/kWh at design power rating and a fuel density of 850 g/L [11], to complete the same driving cycle, approximately 50 L of diesel fuel would have been required. The emissions produced from combustion in a year, considering one duty cycle per day, would total amount to approximately 49 tons. In countries characterized by a high presence of renewable energy sources in the power share of the electric grid, the production of green hydrogen has the potential to reduce or even nearly eliminate CO2 emissions significantly.

4 Conclusions

A retrofit solution for a hydrogen-powered railway maintenance vehicle has been presented in this paper. The main components and auxiliaries system have been designed and tested with a Matlab/Simulink model.

The main results obtained show that:

- the new hybrid hydrogen powertrain is able to provide performance comparable to original diesel locomotive;
- the use of green hydrogen results in an annual reduction of 49 tons of CO_2 emissions;
- for this particular application, a complete electric retrofit presents drawbacks, such as size limitations and technical infeasibility in achieving a comparable range.

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Crafting Symbioses for Mass Deployment Between Mobility-, Charging- and Energy Value Chains

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Abstract. The ambition of the European Union is to achieve climate neutrality by 2050. Electric vehicle (EV) charging can prove to be part of this transition through the use of smart charging and bidirectional charging (also known as Vehicle-to-Anything or V2X). This paper identifies the most important stakeholders in the smart charging ecosystem and investigates their main drivers and objectives in existing and future EV markets. Through this investigation, support for core EU principles, such as a free and fair market based on consumer protection, is bolstered. The analysis shows that stakeholders face a multitude of barriers ranging from economic, to societal, to political. The first section aims to illustrate the overall system architecture of smart charging services, by formulating various roles and business perspectives within different EV related markets. The second section is dedicated to the requirements for the scale-up of smart charging for a number of involved stakeholders by assessing their needs, value cases, and barriers. The third section formulates a preliminary outline of integral requirements on interoperability, communication, and cybersecurity.

Keywords: Smart Charging · Bi-directional charging · mass-deployment

1 Overall System Architecture

1.1 Introduction

New challenges related to grid reliability arise in the European Union due to the intermittent nature of decentralised electricity production and a steady increase in electricity consumption. Electric vehicle (EV) charging can prove to be part of the solution to these challenges through the use of smart charging and bidirectional charging (also known as Vehicle-to-Anything or V2X), the essence of which is to change the time, speed and/or direction of the charging process. End users, system operators, and participants in EV-related markets can all benefit from charging EVs in a flexible way.

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1.2 Stakeholder Landscape

Stakeholders in the smart charging ecosystem face a multitude of barriers ranging from economic, to societal, to political. For EV drivers, the most crucial objective is to grant end customers ownership of EV data, in order to allow them to freely participate in flexible markets. On the manufacturers' end, the lack of a common regulatory framework inhibits the cross-national penetration of EV-related markets. In general, uncertainties in technological advancements, the lack of clear regulatory to deal with flexibility propositions, and delays in market maturation due to a lack of inter-stakeholder dialogues are considered as additional crucial barriers towards the large-scale deployment of smart charging services. In order to tackle these barriers, specific attention should be given to interoperability, data accessibility, and fostering collaboration between stakeholders across the entire smart charging ecosystem.

1.2.1 Charging Infrastructure

The planning of charging infrastructure is a crucial challenge both in the public and private domain [1]. Recent European legislation has led to significant advances in proactive planning of new charging infrastructure, in which data on the (expected) number of EVs, the availability of existing charging stations, and local grid capacity is used to determine in advance which locations require more charging stations [2–4].

Public charging infrastructure installation currently requires coordination between site owners, grid operators, and charging station operators. Ideally, this process will be simplified and completed by as few parties involved as possible. By authorising one party to carry out all three components of the charging station installation, the process could be streamlined and completed within one day [5].

1.2.2 Mobility Services

Mobility is commonly associated with corporate leasing or privately owning a car, but this paradigm is changing in favour of alternatives such as car sharing. New value propositions for mobility services and car sharing can increase the utilisation of cars, reducing parking as well as grid congestion, while also being financially beneficial [6]. Shared fleets and company fleets are electrifying faster than privately owned cars because they drive more kilometres per year and thus have a stronger business case. A larger EV fleet provides more charging flexibility as well as more opportunities for smart charging and V2X integrations.

1.2.3 Charging Services

Data availability is a prerequisite to get the most value out of smart charging, as the optimal charging profile is decided by smart technology and algorithms. Data can be obtained either through statistical analysis of driver behaviour or by asking EV drivers to communicate the expected parking time, the desired minimum state of charge, and the preferred application of smart charging (i.e. as cheaply as possible, using as much renewable energy as possible, etc.). For optimal usage, automated data sharing is desired. This is particularly useful for complex smart charging such as bidirectional charging, in which the current state of charge of the EV battery and the maximum supported charging speed by both the EV and the charging station need to be shared to ensure optimal performance for both the EV driver and the grid.

1.2.4 Energy Services

Changing the charging process from an uncontrolled to a smart way can provide valuable behind the meter benefits for EV drivers at home and at company sites. EV drivers can benefit from electricity prices based on time-of-use tariffs and spot market prices by charging at times when electricity prices are low and feeding back electricity into a home or other building during periods of high electricity prices [7, 8].

Supply and demand of electricity has to be roughly in balance at all times to keep the grid frequency at 50 Hz. Frequency imbalances can lead to power outages and deterioration of and damage to electronic equipment. The EU employs the concept of balance responsibility to ensure a stable grid frequency. Each market participant is responsible for the imbalances they cause in the electricity system. In practice, small-scale consumers such as EV drivers will delegate this responsibility to a balance responsibility party (BRP), which is usually their energy supplier.

2 Requirements of Scale-Up of Smart Charging

The key for EV drivers to make use of smart charging and V2X is availability of and access to important data. EV drivers want certainty that the EV is sufficiently charged at the end of the charging session. Information about the charging session must thus be transparent and communicated clearly. Optimising charging also requires data from the EV and information from the driver, highlighting the importance of open data standards and giving drivers access, at no costs, to proprietary EV data such as the state of charge. In addition, uncertainty with regard to driving range and the state of health of the EV battery have been named as crucial barriers for EV drivers.

2.1 Charge Point Operator and e-Mobility Service Provider

The Charge Point Operator (CPO) and e-Mobility Service Provider (EMSP) are two distinct important roles in the exploitation of charging infrastructure. In many instances, the roles of CPO and EMSP are fulfilled by the same company. A CPO installs and maintains charging stations from one or more manufacturers to enable EV charging. They are responsible for standard operation, maintenance, data sharing, and providing additional functionalities such as smart charging. The EMSP is the contracting party and point of contact for EV drivers when charging at publicly available charging stations [9].

Standardisation of tender procedures of local governments will provide clarity to CPOs for requirements regarding dynamic pricing schemes, as well as smart charging and V2G operability and/or readiness. Further access to transparent information when providing smart charging services is needed as well.

2.2 Distribution and Transmission System Operator

The Distribution System Operator (DSO) and Transmission System Operator (DSO) are responsible for operating, ensuring the maintenance of, and developing respectively the electricity distribution system and electricity transmission system. The DSO fulfils three roles: connecting distributed energy resources and the vast majority of consumers - including charging stations - to the grid, physically transporting electricity flows across the distribution grid, and facilitating the market by managing registration of grid connections and market participants.

Following the EU regulations part of the Clean Energy Package, DSOs are now allowed and incentivised to procure flexible assets in order to maintain system security. EVs capable of smart charging are a potential flexible asset to be deployed by the platDSO in the near future.

TSOs are responsible for the reliable and safe operation of the electricity transmission grid. Safeguarding electricity supply is dependent on the TSO's ability to maintain the grid frequency within predefined boundaries and to ensure that the transmission grid is able to transport the total electricity demand. Daily TSO tasks therefore consist of both resolving grid imbalances via the activation of balancing reserves and preventing exceedances of the technical limits of the transmission grid by applying constraint management.

It is possible that DSO and TSO activities on respectively the congestion management and balancing markets interfere with one another and can cause inadmissible effects on other system operator's activities. Therefore, there is a need for extensive cooperation between system operators. Such cooperation already exists in a number of Member States via market platforms such as Equigy and GOPACS, but legislation on system operation needs to be revised for these new market platforms [10, 11].

2.3 Market Participants

New market participants, such as the aggregator and the flexibility service provider, have emerged in European flexibility markets as the result of European legislation, which requires a minimum bid size for the market.

Market participants are reliant on data accessibility in order to develop market platforms and build sophisticated data models that facilitate the needed inter-stakeholder communication and pricing schemes. Real time EV data is currently proprietary to EV manufacturers and European wide legislation requiring free and non-discriminatory data sharing will likely not be implemented by Member States in the next few years.

2.4 EV and Charging Station Manufacturers

Manufacturers might, in the current market, be hesitant to invest in smart charging and V2X because of the higher investment costs, while not profiting themselves from the unlocked flexibility. Therefore, the transition towards smart charging and V2X necessitates the adoption of an EU-wide policy framework in favour of EV manufacturers. However, the current lack of demand from potential EV buyers for smart charging and V2X functionalities makes it difficult to justify additional investments. A regulatory framework in favour of the automotive sector would at least include measures to increase awareness of smart charging and V2X for end consumers and financial incentives to boost demand, such as tax breaks for 'V2X ready' EVs.

3 Integral Requirements on Interoperability, Communication, and Cybersecurity

In order to scale up smart charging and V2X quickly, attention is needed for open standards and protocols for both hardware and software, as well as connectivity with grid data. Standardisation of tender procedures of local governments will provide clarity to CPOs for requirements regarding dynamic pricing schemes, as well as smart charging and V2G operability and/or readiness.

Ideally, an open charging infrastructure in which all market participants can participate on a non-discriminatory basis will be built. Two types of interoperability are distinguished: hardware interoperability and software interoperability. With respect to these, Figs. 1 and 2 show overviews of the most common EV charging hardware and software standards and protocols in the current market [12].

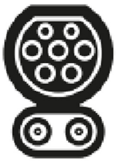
Plug			
Plug name	Type 2 ('Mennekes')	Combined Charging System (CCS) – Type 2	CHAdeMO
Purpose	AC (dis-)charging	DC (dis-)charging	DC (dis-)charging

Fig. 1. Overview of the most used plugs for EV charging in Europe.

Significant attention should also be given to cyber security and privacy. All charging stations together form a smart network of ICT systems and back offices to optimally deploy the use of renewable energy and grid capacity. Charging infrastructure should be open and accessible to everyone: for all kinds of vehicles, software systems, charging protocols and apps, while at the same time being protected against cyberattacks. Cybersecurity in the smart charging chain can be improved by including technical security measures in tender requirements for (public) charging infrastructure and by making cybersecurity an integral part of all communication protocols [13].

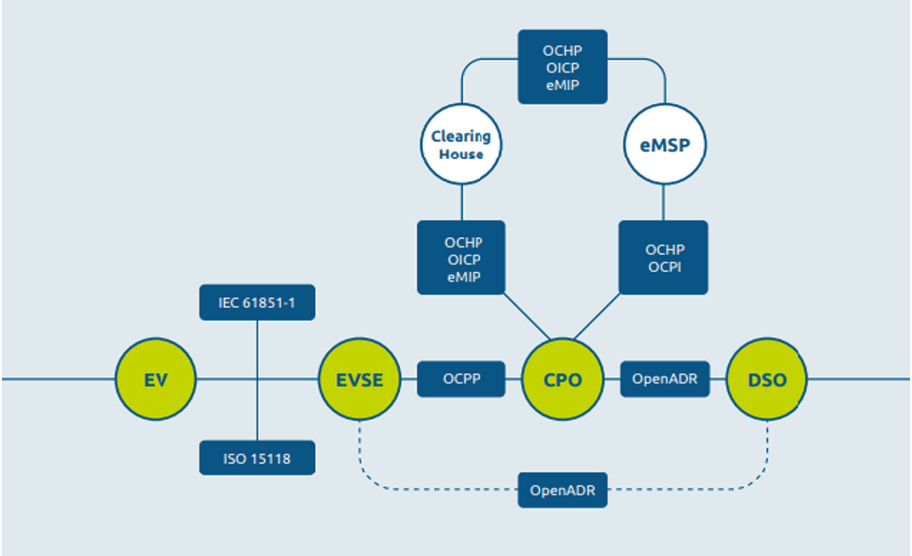


Fig. 2. Overview of the most dominant standards and protocols related to EV charging.

4 Recommendations

To fully unlock the potential of EVs in flexible markets, barriers to enter flexibility markets should be removed. Most notably, prequalification procedures for small-size distributed energy resources should be simplified and EV drivers should be given access, at no costs, to proprietary data.

Tender procedures for (public) charging infrastructure should include a basic set of requirements for smart charging readiness.

A regulatory framework aimed at increasing awareness of smart charging and V2X can encourage manufacturers to implement smart functionalities.

The further development and implementation of widely accepted standards and protocols such as ISO 15118-20 and OCPP should be promoted by European legislation.

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E-mobility Policy Tracker: Understanding the Progress and Gaps in Electric Mobility Policy Measures in Developing Countries

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Abstract. The EU-supported SOLUTIONSplus global e-mobility project, together with the Asian Transport Outlook project - supported by the Asian Development Bank (ADB) and the Asian Infrastructure Investment Bank (AIIB) - have developed an E-mobility Policy Tracker that pursues better understanding of the state of policy measures for accelerating the transition to e-mobility in developing countries which then contributes towards pursuing holistic, time sensitive and context appropriate policy measures and packages.

The E-mobility Policy Tracker focuses on three key areas: vehicles, charging equipment, infrastructure, and the provision of relevant services. The tracker also categorizes policy measures according to the different portions of the e-mobility ecosystem, such as equipment development, infrastructure provision, equipment procurement, service provision, integration, usage, and maintenance. The E-mobility Policy Tracker also considers the wide range of policy initiatives used by governments to encourage e-mobility such as: regulations, institutional measures, partnerships, demonstration actions, informational measures, fiscal incentives and disincentives, and non-fiscal incentives and disincentives.

The paper presents the results of application of the E-mobility Tracker in 16 countries across the developing south (Armenia, Bangladesh, Bhutan, Ecuador, Fiji, India, Indonesia, Malaysia, Nepal, Philippines, Rwanda, Tanzania, Thailand, Uruguay, Uzbekistan, and Vietnam). It reports the current state of policy measures in these countries, as well as priority gaps that need to be addressed in the countries.

Keywords: electric mobility · global south · sustainable mobility

1 Introduction

The changing climate is one of the most pressing challenges of our time. The Intergovernmental Panel on Climate Change has already declared the presence of unequivocal evidence that human influence has warmed the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) estimates that even with the committed (up to October 2021)

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nationally determined contributions (NDCs), it is still likely that global warming will exceed 1.5 °C during the 21st century [1]. It recognizes that there are still gaps between projected emissions from implemented policies and those from NDCs and finance flows still fall short of the levels needed to meet climate goals across all sectors and regions." (IPCC, 2022). It emphasizes that the projected CO2 emissions from existing fossil fuel-based systems, without additional abatement, would exceed the remaining carbon budget towards a 1.5 °C pathway. The IPCC estimates that in 2019, transportation-related greenhouse gas (GHG) emissions accounted for 23% of energy-related GHG emissions. It estimates that the growth in transportation related GHG emissions have not gone down and had remained roughly constant (2% per year) from 2010–2010, in contrast to the decline in the emissions growth in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%) [1].

The International Energy Agency (IEA) estimates that road transportation contributes 74% of the total transport emissions, and up to 18% of the total fuel combustion-related emissions globally. It is interesting to note that these contributions are much higher when we look at the developing countries, particularly in Africa and in Asia [2]. The IPCC, since its fifth assessment report, has emphasized the importance of electromobility for land transport as a key mitigation strategy towards achieving global climate goals. In its sixth assessment report, the IPCC reiterates that widespread electrification of the transport sector is likely crucial for reducing emissions from the transport sector. It highlights that battery electric vehicles (BEVs) powered by low-carbon electricity have lower lifecycle GHG emissions than internal combustion engine vehicles (BEVs). Moreover, BEVs have the additional benefit of supporting grid operations (e.g. electric vehicle – grid integration strategies) [3]. On a lifecycle-basis, electric vehicles powered by low-emissions electricity offer the largest decarbonisation potential for land-based transport [1].

In 2022, electric vehicle sales grew exponentially despite headwinds in economic and geopolitical uncertainty, supply chain disruptions, and high commodity, energy, and logistics costs. Electric car sales (battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) – exceeded 10 million last year, up 55% relative to 2021 [4]. In contrast, sales of internal combustion vehicles have already peaked globally and are in decline. Although the electric vehicle market is expanding, it is still marginal in share compared to the overall automotive market and environment, and further action is needed towards accelerating the transition towards electric mobility.

While the global south is entering the initial adoption phase of electric mobility, with annual sales moving beyond the share of 1% in many countries, some countries have reached the tipping point with sales exceeding 5% share [4]. However, the global literature addressing electric mobility policy measures development has primarily focussed on the global north and some more prominent countries in the global south [5–7]. The authors were also not able to locate specific literature that had looked into specific categorisation exercises for e-mobility policy measures involving developing countries from different regions globally. Further investigation of policy measures being applied in developing countries towards e-mobility transition is needed, as such can provide useful insights for other countries that face similar contexts, resources, constraints, and potentials. The value of such comparative categorisation of policy measures can provide inspiration to governments in such developing countries as to what measures are being applied elsewhere, and how these are evolving.

Recognising the importance of such, the EU-supported SOLUTIONSplus global e-mobility project, together with the Asian Transport Outlook project which is being supported by the Asian Development Bank (ADB) and the Asian Infrastructure Investment Bank (AIIB) - have developed an E-mobility Policy Tracker that aims to organise information on e-mobility related policy measures.

2 Methodology

The development of the e-mobility policy measures tracker is rooted on a recognition that the transition towards e-mobility is laid down on socio-technical systems. The socio-technical systems (STS) theory suggests that systems, and thus the innovations in such systems are hinged on influencing a variety of interdependent technical, as well as social elements [8, 9].

In the realm of e-mobility policy measures, the utilization of such a STS theory enables a holistic lens to examine how policy measures are evolving, and how the different socio-technical elements are being accounted for. A structure postulating that e-mobility policy measures- and the gaps- can be better understood by dissecting them in terms of pillars, stage in the value chain, and type of measure, as inspired by the STS theory. Aside from capturing "pillars" of socio-technical systems, the structure shown in Fig. 1 below also captures the "stages" involved in e-mobility, as well as the categories of policy measures, so as to bring additional This structure can further be detailed by incorporating other layers depending on the purpose of the analysis.

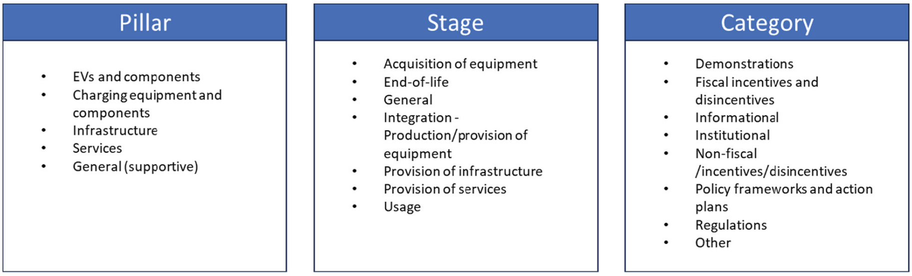

Fig. 1. Structure Used in Classifying the Policy Measures

After the definition of the structure, the researchers listed down an initial list of policy measures and categorized them according to the categories provided for each of the layers. A policy measures stock taking exercise was then conducted for the following countries: Armenia, Bangladesh, Bhutan, Ecuador, Fiji, India, Indonesia, Malaysia, Nepal, Philippines, Rwanda, Tanzania, Thailand, Uruguay, Uzbekistan, and Vietnam. These countries had been selected as part of the contribution to the priority countries of the SOLUTIONSplus project, and the ATO project. Additional policy measures are included in the list in case these are discovered from the stocktaking exercise. The exercise provides novel insights as to the types of measures that are actually being prioritized in the developing countries, as well as the nature of the level of priority that is given to specific policy measures.

3 Results and Discussions

Based on the analysis of the 16 countries, two hundred twenty-two unique policy measures were noted down through the exercise. It is important to note that 49% of these are policy measures that focus on electric vehicles (EVs) and EV components (Table 1 and 2).

Table 1. .

Pillar	Number of Unique Policy Measures
Charging equipment and components	31
EVs and EV components	109
General	42
Infrastructure	31
Services	9

In terms of the individual policy measures, renewable energy targets have been documented for all the countries. Custom tariff waivers/reduction came in second and had been noted for 15 out of the 16 countries.

Table 2. .

Pillar	% of Countries
Renewable energy targets	100%
Custom tariff waiver/reduction for EV and components	81%
Dedicated National EV Policy/Roadmap/Strategy	69%
Excise tax waiver for EV and components	56%
Import tax exemption/reduction - raw materials, supplies, components	56%
Value-added tax waiver or reduction for EV and components	56%
EV Modal targets	56%
EV included in NDC	56%

The graph below depicts the overall distribution of policy measures across the different countries. It is quite clear that the focus has been on supporting the provision of

EVs and EV components. Sixty percent (60%) of the documented policy measures were on this pillar. Policy measures focusing on charging equipment and components only accounted for 11% of the measures, while infrastructure-focused policy measures only accounted for 10% of the total. Policy measures focusing on supporting the acquisition of EVs exhibited the most number of observations in Africa, Latin America, Pacific and South Asia. In Southeast Asia, policy measures towards supporting the production/provision of equipment were most prevalent. In terms of the categories, regulations came first, accounting for 33% of the overall policy measures that were observed, and fiscal measures accounted for 29% of the total (Fig. 2).

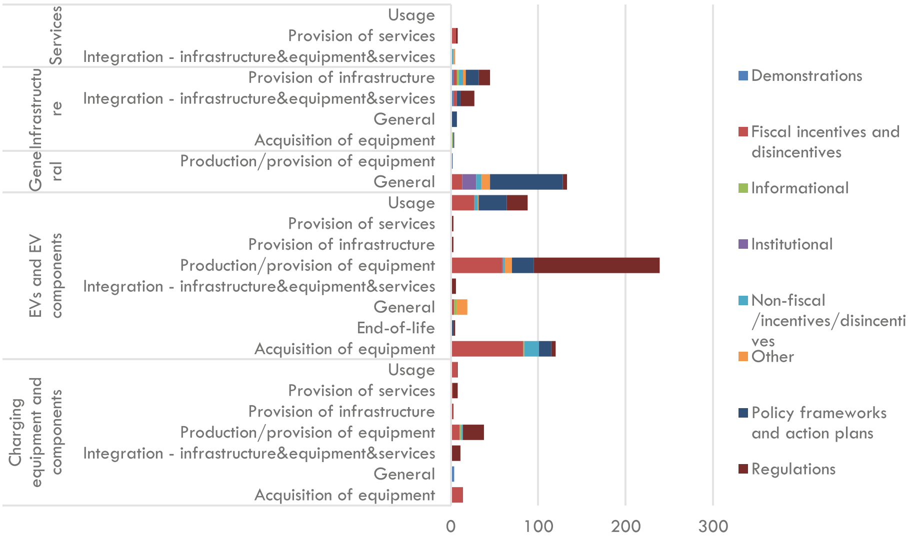

Fig. 2. .

4 Conclusions

The study has done an extensive stocktaking of e-mobility policy measures in 16 developing countries across the globe, with the database containing 800 individual measures for 222 types of policy measures. The stocktaking exercise shows that governments have been focusing more policy measures that focus on the EVs and its components. Policy measures focusing on supporting the production / provision of electric vehicles (and EV components) have been documented the most if we combine the measures from all the countries. In particular, regulations that govern such provision of EVs and EV equipment accounts for 70% of the measures that had been documented under this policy measures category.

The exercise contributes to the existing literature by unveiling the commonalities of the policy measures and packages that are being employed towards e-mobility transition across the different developing countries as well as the common priority gaps.

While the stocktaking exercise provides novel insights in terms of the types of policy measures are being implemented across the globe, further analysis is needed to unveil the nuances related to the magnitude of progress of the countries in specific measures. For example, assessing and comparing the level of fiscal incentives being implemented in the different countries would reveal significant insights which go beyond identifying the types of policy instruments that are being implemented in the countries.

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Assessing the Adaptability of EVs, a Case of Visakhapatnam

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Abstract. Climate change is a pressing global concern, largely driven by greenhouse gas emissions, particularly CO_2. The transportation sector contributes 22% of global CO_2 emissions. As of 2022, EV penetration in India was only 2–3%, indicating challenges in EV adaptability even after policy action. The research aimed to identify and address variables affecting EV adaptability. These factors were categorized into Technological characteristics, Socio-economic characteristics, Travel Patterns, and User Challenges. Surveys of EV users and operators were carried out in Visakhapatnam, a pilot city for EV initiatives in Andhra Pradesh. Key findings revealed three main issues hindering EV adaptability: lack of workplace charging facilities, uneven spatial distribution of public charging stations, and the absence of a common platform to access charging infrastructure. Proposed strategies to bridge these gaps include creating city-level charging infrastructure plans, mandating workplace charging through building bye laws, and establishing an integrated platform for charging access. This research offers valuable insights to enhance the electric mobility framework, highlighting specific roles to stakeholders in addressing the identified issues. It serves as a steppingstone in achieving cleaner, more sustainable transportation and reducing CO_2 emissions from passenger vehicles, which contribute significantly to global climate change.

Keywords: Electric Vehicles · Adaptability · Stakeholders · Institutional Framework

1 Background

GHG emissions play a major role in climate change. The Transport sector contributes to 23% of Global GHG emissions, which is more than any other end use sector. In the global scenario, on road vehicles account for 77% of the transport CO2 emissions [1]. In the absence of further policy action, GHG emissions is expected to rise around 20% by the year 2023 and 50% by the year 2050 [2]. As per the International Energy Agency, at least 20 percent of all road transport vehicles globally to be electrically driven by 2030 in order to limit global warming to 2 degrees or less. Commitment to broaden the partner countries' efforts and call for a decisive joint effort towards sustainable transport electrification [2]. EV 30@30 – Global level and India's 2030 vision on electric vehicles, both aims to target 30% EV penetration by the year 2030 [3]. Most of the states in India

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have also framed their respective state EV policies. Still, even after the policy action, as of 2022, the penetration of EVs in India stands at 2–3% of total on road fleet. This research aims to identify the factors concerning the adaptability of EVs in the local scenario which helps identify the roles and responsibilities of the stakeholders. The study focuses only on the 2W EV users as well as 4W EV users to identify the challenges faced in utilizing the EVs.

2 Literature Study

2.1 Schemes/Policies/Missions

National Level. In 2011, National Council for Electric Mobility (NCEM) has been formulated as an apex body for electric mobility in India. This is one of the key steps in addressing the need for paradigm shift for electric mobility in the country. Further there have been several initiatives in this domain as shown in Fig. 1.

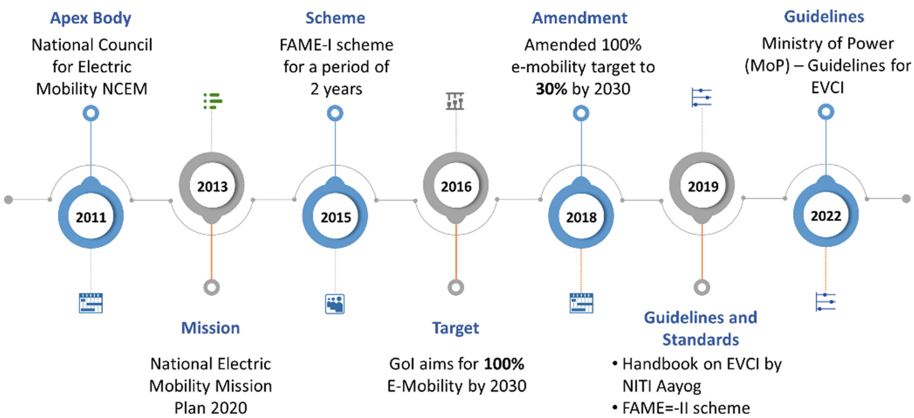

Fig. 1. Timeline for various initiatives by the policymakers and regulators in India

The initiatives mentioned in Fig. 1 have been reviewed as part of literature to understand the mechanism and the roles of various organizations at the national level.

State Level. The 'Electric Mobility Policy for 2018–2023' for the state of Andhra Pradesh highlights the benefit covering areas which include Manufacturing, Charging Infrastructure, Demand creation, Research & Development (R&D). The target of this policy is for AP to be one amongst the best three states in India by 2022, and the best state by 2029 and the leading global investment by 2050. The policy also highlights the incentives the government will offer to the EV buyers, manufacturers and charging providers to enhance the adoption and development of EVs [7].

2.2 Research Papers/Journals/Articles

Research have shown that the factors which influence the adaptability of EVs are diverse in nature ranging from the Awareness, User characteristics, vehicle characteristics, Infrastructure availability, Environmental Concern, Finance, Government Policies [5, 6].

The factors identified from the literature have been classified under four heads for the User Survey namely Technological characteristics, Socio-Economic characteristics, Travel Pattern and User Challenges.

The Technological characteristics implies the Battery Capacity of EVs, Range of the EV, Charging time, Charging Modes available. The Socio-economic characteristics include the Age, Gender, Income, Occupation, Qualification. The Travel Pattern and User Challenges include the Daily KMs driven, purpose of utilizing EV, Availability of Workplace Charging, Usage of Public charging facilities and their availability, Queue length at the public charging facilities.

3 Site Study

Under the FAME-II (Faster Adoption and Manufacturing of Electric Vehicles) scheme, the government of India has allocated a significant number of charging stations to various states. Andhra Pradesh has been allotted 266 charging stations, making it the second largest recipient of charging stations under the scheme. As part of the AP state EV Policy, four cities in Andhra Pradesh have been declared as model Electric Mobility (EM) cities. These cities are Tirupati, Visakhapatnam, Vijayawada, and Amaravati. Among these cities, Visakhapatnam has been chosen as the pilot city for all the initiatives and measures implemented under the state policy [7]. One of the key criteria for selecting the study area for research purposes is the availability of EV charging infrastructure. Considering this, Visakhapatnam is selected as the study area for the research.

4 Data Collection

The Secondary data collected includes operator survey and the data collected from various sources to support the research. The operator survey is done to locate the charging facilities, the details of the charging stations including the connector type, operator, capacity of the EVSE and the tariff for utilizing the facility. The primary data collected from the site encompasses the EV user survey. The EV user survey was conducted using a structured questionnaire and is divided into several categories to gather comprehensive information. The EV user survey followed a random sampling technique in the Greater Visakhapatnam Municipal Corporation limits. A total of 87 eV users which include 61 2W users' and 26 4W users' data has been collected for the assessment.

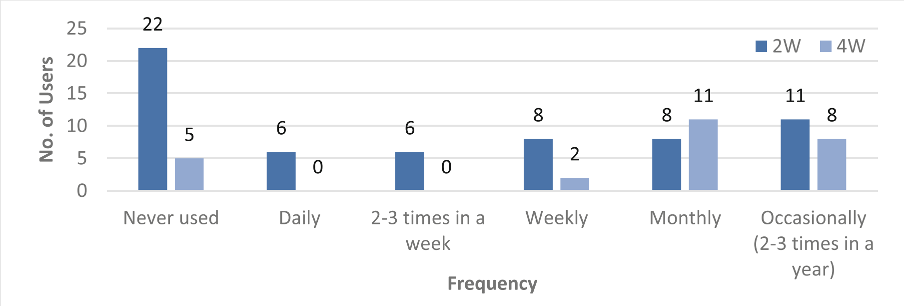

Fig. 2. Mode wise frequency of public charging by EV users

5 Data Analysis and Findings

5.1 EV User Survey

It is observed from Fig. 2 that nearly 36% of 2W EV users have not used public charging stations at least once. One of the reasons can be that only Ather company has installed DC fast charging stations for 2Ws. 73% of EV 4W users use public charging facilities on monthly basis or occasionally.

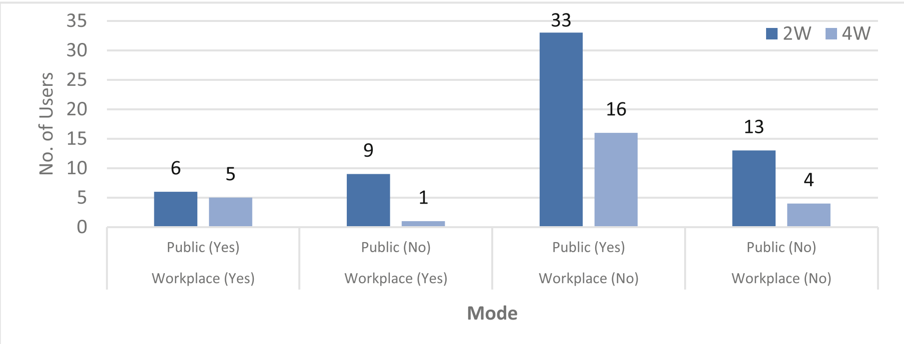

Fig. 3. Availability of charging at workplace vs Utilization of public charging facilities

It is inferred from Fig. 3 that around 56% users who do not have access to workplace charging have utilized public charging facilities (49 out of 87) which highlights the need of workplace charging facilities.

The data collected is the average number of Kms the user had to take detour from his normal trip to avail the public charging facility when needed. The data in Fig. 4 indicates the lack of spatial distribution of public charging facilities for EVs. In the Urban areas, at least one public charging station needs to be available within a grid of 3km * 3km [4]. Spatial analysis has been carried out using GIS as a tool to verify the spatial distribution of charging facilities in Visakhapatnam (Fig. 5).

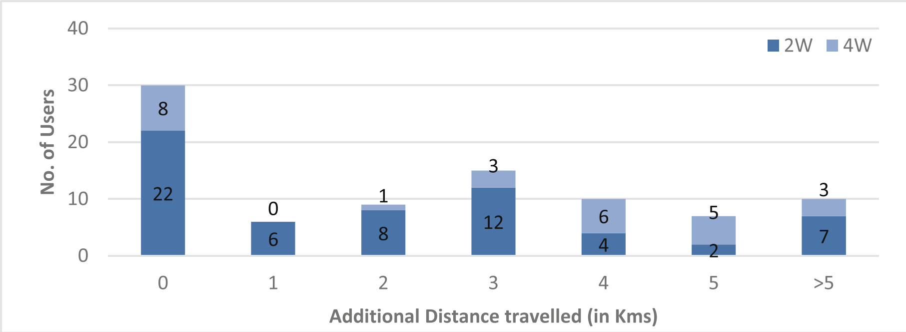

Fig. 4. Average additional distance travelled to avail public charging facilities

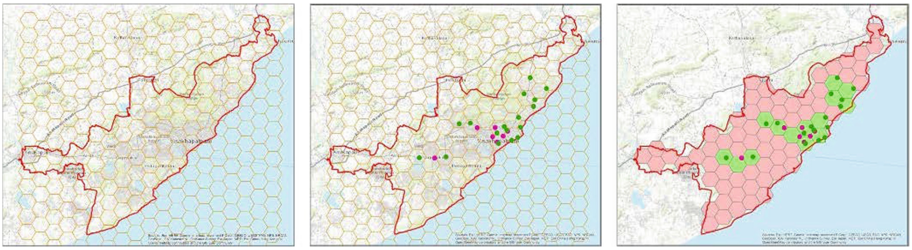

Fig. 5. Spatial Analysis using GIS as a tool to verify the spatial distribution of charging facilities

Currently there are only 26 public charging stations available and are not evenly distributed – 26 charging stations distributed in 14 grids. Most of the charging stations are available in the city centre where land is a constraint which is an anomaly.

The variables have been assessed from the EV user survey to find out the relation between the socio-economic characteristics, travel pattern, demand for charging other than home charging and also to find out the challenges faced in the utilization of electric vehicles. It is found that income range is one of the relevant factors for owning an EV and the most common purpose for utilizing an EV is for the Intra city travel for the job/work purpose and nearly 80% of the users do not use their EV for intercity travel due to lack of charging infrastructure and range anxiety. It is found out that nearly 73% of the 4W EV users require the public charging facilities on monthly basis. Also, it is found that the workplace charging, and the public charging are both correlated as the users who do not have access to workplace charging are more likely to use the public charging facilities. Further, the most common challenges faced by the EV users are the range anxiety, limited availability of public charging stations and identifying the queue at the available public charging stations.

5.2 Institutional Mapping

The stakeholders concerning electric mobility in India can be categorized into different levels: national, state, and local. Each level comprises various ministries, departments, organizations, and statutory bodies that have taken policy actions and initiatives related to electric mobility starting from the local level to national level.

5.3 Findings and Recommendations

Three major issues have been identified from this research. The first issue is the absence of workplace charging facilities. This can be addressed by amending the building byelaws at state level, mandating the provision of charging facilities in the parking areas for non-residential land uses. This helps reducing the demand for public charging facilities. The second issue is the uneven spatial distribution of public charging facilities. This can be tackled at the ULB (Urban Local Body)/UDA (Urban Development Authority) level i.e., at the local level, by preparing a Charging Infrastructure Plan using GIS as a tool to evenly distribute the FAME-II allocated charging stations. Finally, the third finding is the abscence of common platform to access the charging facilities, which does not encourage the user-friendly behaviour for a smooth transition towards EVs from Internal Combustile Engine (ICE) vehicles. There is a dire need to address this issue at the national level by providing a common platform to access public charging facilities, integrating the multiple platforms provided by the private entities for their customers to find vacant charging slots within their reach.

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Development and Implementation of (More) Sustainable and Resilient Electric Vehicle Charging Infrastructure in Public Buildings

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Abstract. The PROBONO project has as main objective to produce validated solutions for the design, construction and operation of zero-emission and positive-energy buildings in sustainable green neighbourhoods through targeted interventions in six different Living Labs (Madrid, Dublin, Porto, Brussels, Aarhus, and Prague). In the Dublin LL, energy efficiency is addressed from multiple perspectives, being one of them to deploy a sustainable mobility infrastructure perfectly integrated with the buildings' power grid that is able to optimize demand and supply of energy in order to maximize renewable energy use and reduce overall energy consumption. To this end, several technologies will be put in place: bi-directional chargers with V2G capabilities to allow the EV fleet of the LL to be charged in the most flexible way possible, deployment of alternative charging solutions such as battery swapping for the e-bike fleet or inductive charging for the vehicles, and second life battery banks to help minimize demand peaks during the day. All these features of the infrastructure will be managed by a secure software platform that enables optimal energy use while reducing the total cost of ownership of the charging infrastructure.

Keywords: Green Building Neighbourhood · Living Lab · net-zero · bi-directional charging · inductive charging · second-life batteries

1 Introduction

In the framework of the European Green Deal, a Green Building Neighbourhood (GBN) can be understood as a set of green buildings integrated at delimited areas or at district level with green energy solutions and green mobility management, as well as appropriate infrastructure supported by policies, investments and stakeholders' engagement and behaviours that ensures just transition and maximises the economic and social co-benefits, given a district profile. Delivered in the right way, GBN infrastructure is a key enabler of inclusive growth, can improve the accessibility of housing and amenities, reduce poverty and inequality, widen access to jobs and education, make communities more resilient to climate change, and promote public health and wellbeing.

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The PROBONO project [1], an EU-funded initiative (Grant Agreement nº 101037075), provides five GBN Transition Acceleration Enablers, deployed through six high impact Living Labs (LLs) in different European cities (Madrid, Dublin, Aarhus, Brussels, Prague, and Porto). Each of the PROBONO Living Labs has its own ambition and scope. Each of them will provide both an experimentation and innovation environment and testbed for GBN innovative solutions. A different mix of technologies, construction/renovation innovations and co-creation aspects are being developed under a single optimum adoption scenario for each Living Lab. Indeed, it is expected that the outputs achieved will be incorporated into a transferability and innovation replication framework, which will enhance the transition capabilities of local communities across Europe (Fig. 1).

Fig. 1. Green Building Neighbourhoods interventions within PROBONO [1].

In order to meet the standards required for a GBN, the PROBONO Living Labs cannot consist only on the development and demonstration of technologies in the LL environments, but also interventions have to be put in place aiming at increasing user acceptance, as well as promoting behavioural changes to maximize impact. Thus, they are user-centered, iterative, open-innovation ecosystems operating in a delimited area, integrating concurrent research and innovation processes within a public-private-people partnership. The stakeholders will 'collectively' co-design solutions and GBN measures for the LL to promote good habits and good behaviour in local context.

One major intervention in the PROBONO LLs, and more specifically in the Dublin LL, is to design and deploy a flexible Electric Vehicle (EV) charging infrastructure that is smoothly integrated into the overall electric grid. The energy system of the buildings will become smarter and will provide flexibilities to the energy grid (e.g. controlled EV charging, integration of batteries, demand response, etc.). The PROBONO LLs (and particularly the Dublin LL) will adopt a systemic approach to the mobility-energy system, establishing the ground for data-driven modelling and GBNs design. Decision Support, optimisation, monitoring and control of the GBN will be achieved through the LLs Digital Twins.

2 The Dublin Living Lab

Dún Laoghaire-Rathdown County, DLR, is a coastal suburban town south-east of Dublin city and the traditional port of arrival of cross-channel ferries from Wales (see Fig. 2). It has the benefit of unparalleled access to public transport, employment opportunities, leisure facilities, education, shopping and an attractive public realm. Dún Laoghaire is undergoing a transformation in terms of use, business types and town design. The County Development plan for 2022–2028 is being reviewed and contains clear climate targets for building usage which will be incorporated into PROBONO.

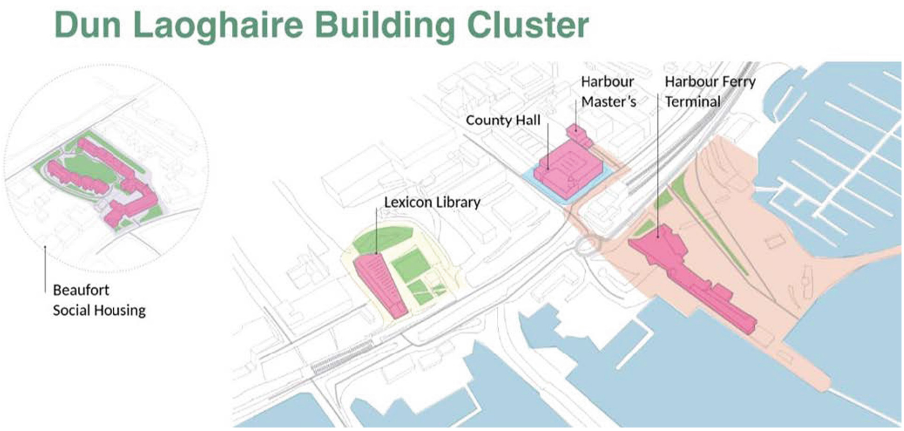

Fig. 2. Dún Laoghaire-Rathdown County (DLR) overview. Image courtesy of UCD and DLR,

The Dublin LL is envisioned as a sustainable and cost effective, zero-carbon GBN, networking key municipal buildings and optimising prototypical housing retrofit for future, wider replication. The LL will engage local citizens in the design and development of a green town centre and living neighbourhood. Improvement of the energy performance of buildings is a primary target for the Dún Laoghaire-Rathdown County Council (DLR), with challenges identified around energy inefficiency in older municipal buildings.

The primary objectives of the LL are to:

- Engage local citizens in the development of an active GBN,
- Evaluate major energy consumers and potential producers to enable dynamic matching of local renewable generation and neighbourhood consumption,
- Undertake analysis of town centre municipal buildings, and housing to identify potential efficiency enhancement,
- Identify optimum strategies for retrofit in the context local climate,

- Undertake retrofit of key buildings, engaging staff, and building users in the process,
- Undertake analysis of pre- and post- retrofit intervention in community housing,
- Engage the community in retrofit strategy and larger sustainability aims to achieve long term sustainable neighbourhoods, and key precedent for other neighbourhoods.

The development of the integrated EV charging infrastructure will be deployed in the County Hall (Fig. 3). This building is the flagship building of the PROBONO LL, and is the headquarters of the Local Authority. The building is extremely energy inefficient and therefore offers huge potential to radically improve energy use.

Fig. 3. Dún Laoghaire-Rathdown County Hall. Image courtesy of UCD and DLR,

3 Development of an Integrated Electric Vehicle Charging Infrastructure

Either public or private, the planning of charging infrastructure (mainly sizing and placement) must satisfy two main requirements: satisfy the mobility demand and at the same time be cost-effective from an operational perspective [2]. It is a fact that EVs put a strain on existing power grids, especially at the low-voltage levels. But it is also true that EVs can offer high flexibility with respect to charging times, charging duration and charging method. Hence, intelligent control of the charging infrastructure and its processes can help to avoid power grid overload, facilitate a higher use of renewable energy, and also increase user acceptance of sustainable mobility modes [3].

In this regard, the current EV charging infrastructure available at the County Hall is relatively outdated (Fig. 4): existing chargers are only unidirectional, and there is no method of storing energy to optimize energy supply for EV charging purposes. To increase the sustainability and the resilience of the charging infrastructure in the event of an energy crisis, several partners (CIDAUT, BOVLABS, BEEPLANET, and UCD) are

Fig. 4. Current EV charging facilities located in the County Hall basement. Image courtesy of UCD and DLR,

devoting efforts to develop a bi-directional charging station with efficient energy storage by using reused batteries.

The smart EV charging infrastructure under development within Dublin LLs contains several interventions involving physical and digital assets, and pursues a threefold objective: enable net-zero emissions operation, achieve a reduced Total Cost of Ownership compared to the original scenario, and ensure secure operation of the system. To this end, bi-directional charging solutions will be installed that will enable real Vehicle-to-Grid (V2G) operations, what will help to reduce operation costs thanks to smart charging of vehicles while at the same time preserve the health of vehicle's batteries along their lifetime. The installation of bi-directional chargers entails several challenges compared to conventional charging solutions. For instance, it requires the setting up of dedicated electric lines that link the vehicles to the power grid. Besides, V2G technology is still in an early stage of development, so the landscape of available chargers ensuring compatibility with the vehicles available in the DLR is low, and installation costs are high. For those reasons, a study on stored energy that can be given back to the grid during off-duty times will also be carried out, in order to detect the risk of complete or partial discharge of the vehicles under certain conditions to establish mitigation measures.

Moreover, alternative and complementary charging options such as static inductive charging will also be explored to increase the flexibility of the charging infrastructure. The smart charging strategies will be supported by the installation of a 145 kWh energy storage system made up of second life Li-ion batteries coming from End-of-Life vehicles. This supplementary energy storage will be used mainly for programmed charging of EVs, helping to smooth peaks of energy demand along the day. The operation of the whole system will be governed by a software platform that will allow integrating charging points management system with the overall building energy management system, in such way that flexibility is maximized on the demand side. The platform will also cover any cybersecurity concerns, ensuring secure transactions between the vehicles and the battery bank and full traceability with Ethereum-based Blockchain, and also implementing Internet-of-Things (IoT) solutions and key edges of the network with edge computing and deep learning capabilities to enhance security and enable scalability (Fig. 5).

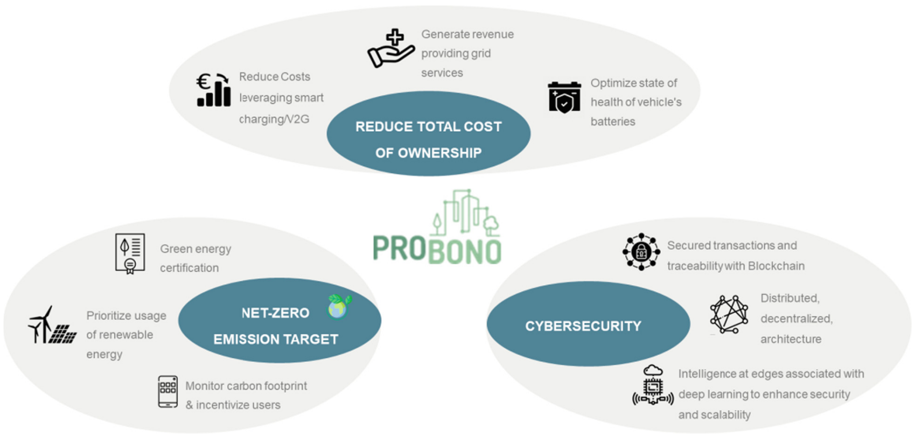

Fig. 5. High-level objectives and functionalities of the EV charging infrastructure.

4 Conclusions and Next Steps

The infrastructure development is still in the design phase that is expected to be completed by mid-2024. All its elements will be located in the basement of the County Hall, where the current infrastructure is located along with the planned second life battery bank. The technical requirements of the system and the potential constraints have already been identified. All these important aspects are being considered in the design stage to ensure a smooth operation of the technology once deployed. Once the design stage is finished, and in parallel with the implementation stage, the integration of the EV charging platform into the overall PROBONO digital twin will be explored, to allow displaying charging-related information in a dashboard that can be exploited by the building managers or any other stakeholder.

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Optimal Integration of Electric Vehicles for Rural Micro-Grids in Ireland

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Abstract. Electric vehicles (EV) and local renewable resources provide a potential for substantial decarbonization of the transportation sector. A large number of electric vehicles have the potential to decrease the pressure of the existing electricity network and can significantly balance the amount of extra non-stored renewable energy generated in the market. However, mass adoption of electric vehicles also requires charging infrastructures and charging hubs. Solar photovoltaics-EV and wind-EV are two recommended options for Ireland considering country's present energy state and high penetration of renewable energy sources such as wind, wave, and solar photovoltaics. Three domestic scenarios are investigated: Integration of solar photovoltaics with EVs; Integration of wind energy with EVs; and a hybrid system. In this research, the size of a charging station is optimized based on each scenario. A comparative study is carried out between the different configurations with regards to CO_2 emissions and annual energy charges. The feasibility of integration to the grid is analyzed as the grid-connected scenario. The optimal cost and emission for the hybrid PV/wind system includes the installed capacity of both renewable sources as well as the power transferred to the grid. Those variables are reflected in the annual energy production and levelized cost. Finally, the best option in terms of both cost and energy reliability is evaluated for each scenario.

Keywords: Electric vehicles · Ireland · Vehicle2Home · Integration · Microgrid

1 Introduction

1.1 Home-to-Electric Vehicle

By switching to less environmentally harmful fuels, electrified air conditioning and heating systems, and implementing energy-saving and sustainable energy technology, homes may significantly reduce their impact on the environment [1]. Renewable technology adoption by households, including rooftop solar, electric vehicles (EV), and wind turbines, is accelerating. This growth is visible from the top-down regulation including governmental and financial tools, as well as bottom-up mechanisms including the social diffusing effects. Lowering energy costs and the health effects of pollutants in the air are two ways that households may directly benefit from this development [2].

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Parallel to this, mounting solar photovoltaics (PV) on independent homes' roofs for utilization in refrigeration, heating, and other personal electricity needs has grown in demand. Prospective electricity needs might be partially solved if homeowners were encouraged to deploy a greater number of powerful PVs in order to boost their energy generation and be able to recharge their battery-operated EVs. It is necessary to resolve both technical and policy concerns for this to become feasible. The problem is that the growing percentage of fluctuating power output is not resolved by the current method, which involves connecting PV to the grid and so reducing the discrepancies between consumer demand and PV generation. Combining PVs with another energy generators such as wind turbines or storage facilities might serve as an option [3].

The creation of guidelines and a home energy control system for grid-tied residential dwellings with solar photovoltaics and battery energy storage systems was the subject of a study in [4]. However, in this instance, there was no consideration given to the time of use for pricing as part of the utilization of EVs in the framework. A design model for a microgrid with solar, battery, diesel, and wind turbines connected to an electric vehicle with varying tariffs was put forth in [5]. The lack of rules, nevertheless, makes the research less helpful for users and prevents the development of a rule-based energy management system. In References [6] and [7], the connection of EVs to the electric grid was taken into consideration when determining the best way to plan a direct current (DC) microgrid as a supply network. However, as it weakens the EV's battery, this mode of integration is not recommended for home users.

1.2 Aim of the Current Study

This study sets out to numerically determine whether having solar photovoltaic and small wind generation as well as their combination enhances the performance of a building integrated EV charging station in terms of satisfying the demand subject to the minimized cost and emission.

The indicators of assessment to gauge an EV's involvement as stored energy for a home with PV/wind include:

- increased PV/wind energy production involving the impact of load leveling;
- reduced CO2 emissions (on utility-supplied electrical power utilized at household);
- potential cost savings/income (depending on to purchase/sales tariff).

2 Methodology

The grid-connected PV-wind-storage microgrid system consists of PV modules, wind turbine, battery packs, converters, and the electric vehicle as depicted in Fig. 1. The initial objective function in this study endeavor is the reduced annualized system expenses (net present cost), which is carried out as:

$$C = P_{PV} C_{PV} + N_{wind} C_{wind} + N_{bat} C_{bat} + P_{inv} C_{inv} - C_{rev} \tag{1}$$

In Eq. (1), C represents the total net present cost, N represents number of components, and P represents output power. C_{rev} represents the income made by selling the excess electricity back to the grid. Indices *PV*, *wind*, *bat*, *inv*, and *rev* represent costs for photovoltaic panel, wind turbine, battery packs, inverter, and revenue due to selling electricity to the grid. Purchasing electricity from the grid for charging the electric vehicles is prohibited. For any component i of the system, the following costs are already included in Eq. (1):

$$C_i = C_{capital} + C_{maintenance} + C_{operations} + C_{replacement} - C_{salvage} \tag{2}$$

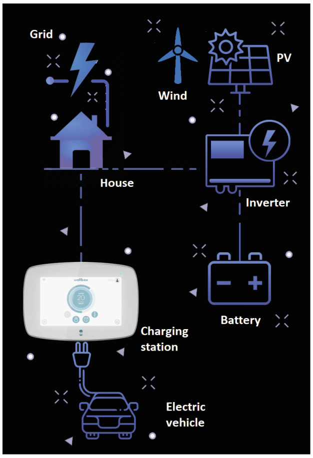

Fig. 1. Topology of the PV/wind grid-connected electric vehicle charging scheme

To calculate the annualized cost of each component, the capacity recovery factor is defined as follows as a function of years n and annual interest rate i. For each cost in Eq. (1), the total cost over the lifetime is multiplied by *CRF* to obtain the total net present cost [8]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

The second objective was to minimize life-cycle pollutants, according to this definition. It involves the CO_2 operating emissions caused by the energy expended during the whole process of installment and operation. It is calculated based on the Eq. (4) where E represents the emission for each component i and f denotes the penalty for equivalent CO_2 emissions generated by that component:

$$Emission = \sum_t f_i E_i \tag{4}$$

The levelized cost of energy, which is expressed by the subsequent equation, is the mean expense per kWh of electricity produced by the whole system.

$$LC = \frac{C}{8760 \times P_{total}} \tag{5}$$

Data related to the solar insulation, solar clearness index, local temperature, and wind speed at the location of the charging station is obtained from NASA worldwide energy resource [9, 10] database. Different steps for the optimization process are summarized in Fig. 2. Linear programming is used to find the minimized total cost. In the first step, the hourly weather data is used to generate hourly PV and wind outputs for various sizes considering their capacities and constraints to cover the load. At this step the emission is calculated and it is added to the total cost as the penalty. Then the mismatch is the identified by introducing a range of battery storage options and their cost is included as part of the total cost. Finally, by generating and comparing different combinations, the minimum costs are extracted as the solution to the problem.

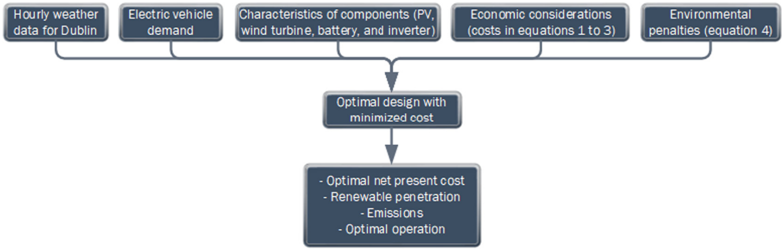

Fig. 2. Topology of the PV/wind grid-connected electric vehicle charging scheme

3 Results and Discussions

Figure 3 shows the results of the optimization where the best solution in terms of minimized cost is the PV-driven system. This scenario has the total net present cost equals to €26440 (= $28680) excluding the Irish energy grant. Not all the points shown in Fig. 3 are feasible in terms of the constraints and the real optimal solution is depicted by an arrow. It equals to €24500 (= $26580) considering the home PV-installation grant [11]. This scenario represents 24 batteries connected to a 5-kW PV array. The batteries provide an excellent input-output operation as 2769 kWh energy charged them while 2379 kWh is discharged. The difference represents the electrical losses per year. The

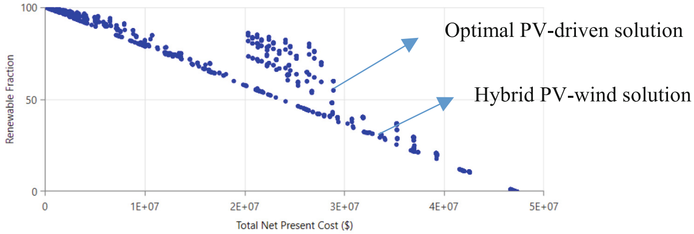

Fig. 3. Distribution of the optimization results as functions of renewable fraction and total net present cost

hybrid PV-and-wind scenario has the total net present cost equals to €30410 (= $32990) in Fig. 3 while the wind-driven is not recognized as the optimal solution due to the high investments and its non-continuous capacity. The PV-driven system saves 19% in cost. The hybrid system saves almost 9% compared to a regular charging hub.

Figure 4 compares the total costs in Eq. (1) for different components. More income is created in the hybrid design, while the batteries impose the highest initial and replacement costs on the system.

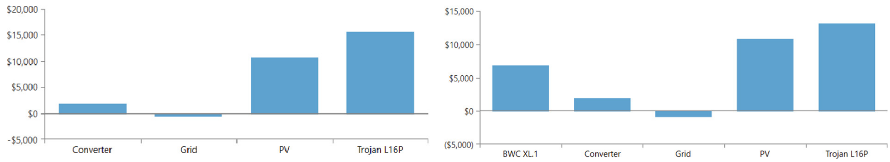

Fig. 4. Comparison of different costs associated with PV-driven (left) and hybrid (right) charging station designs

As Fig. 5 illustrates, adding the wind generator can extend the feed time of charging as well as providing more opportunity to sell back electricity at peak times to the grid. The complementary operations in summer and winter are evident from the right figure.

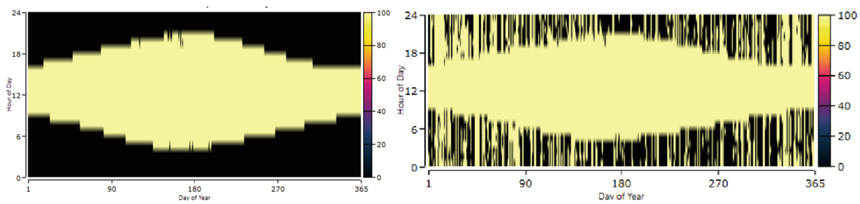

Fig. 5. Instantaneous renewable output divided by generation for (left) solar-drive and (right) hybrid charging station designs.

Variations of the different components for two designs are illustrated in Fig. 6 where more production and smoother operations is clearly visible to satisfy the electric vehicle loads. Both systems are capable of reducing 3207 kg equivalent annual CO_2 emissions.

In Fig. 7, the hybrid scenario provides a more compact distribution with smoother operation of the demand where a semi-linear correlation is clear with higher loads.

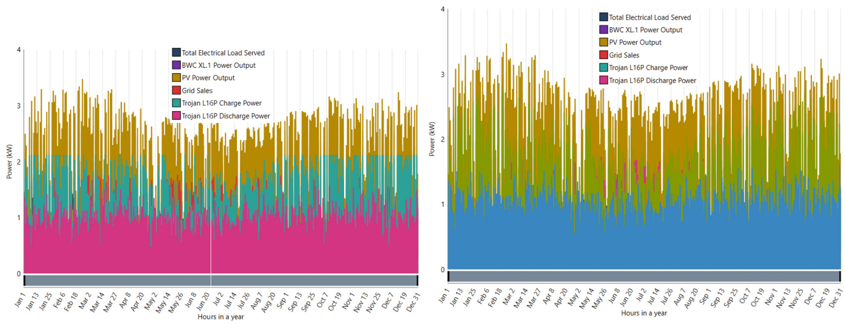

Fig. 6. Energy balance between input-output components and the charging station load for the hybrid (left) and the PV-driven (right) systems.

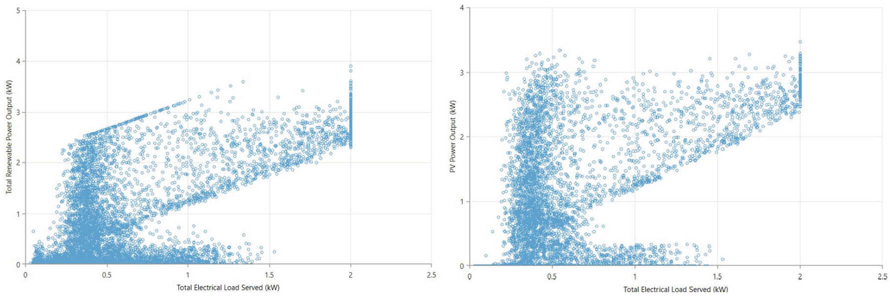

Fig. 7. Charging station loads vs. generation for the hybrid (left) and PV-driven (right) systems.

4 Conclusions

An optimization procedure is suggested in this study to design and compare the economics and performance of an integrated charging station. The suggested system architecture provides a stand-alone charging station powered by the PV and PV/wind driven designs as compared to a regular charging station powered by the grid only. The hybrid design shows 15% higher cost while this increase can be removed if the restriction for the daily selling capacity to the grid is improved. Battery storage was fully operational in both designs where the charging and discharging cycles were done up to the threshold provided. The design hybrid system did not take advantage of all capacities for all components. Both systems could achieve a maximum CO_2 reduction of 3200 kg in a year. In other words, a grid-connected design has the potential to detach and run independently when Irish severe weather sometimes impairs the stability of the conventional grid, providing crucial energy resilience for rural areas in need. Since the optimization is performed based on the deterministic behavior of both sources and the charging station load, it is also recommended to include the stochastic behavior of EV demand to perform a stochastic optimization as it helps a more realistic prediction of the system performance.

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Methanol as a Fuel in Shipping: Review and Outlook to ICE Research Within MENENS

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Abstract. Waterborne transportation has long been the backbone of global trade, with the reciprocating internal combustion engine (ICE) as the dominant power source. In the efforts to decarbonize shipping, methanol has emerged as a promising alternative fuel due to its easy storability and favorable combustion characteristics compared to non-carbon fuels such as hydrogen and ammonia. In the MENENS project, one of the research objectives is to better understand, further develop, and demonstrate different engine technologies that can employ methanol fuel in marine-sized engines. This study reviews maritime stakeholder research on methanol fuel for marine ICEs, emphasizing the chosen injection and ignition strategies across different engine technologies. In this paper, we aim to identify research gaps concerning methanol as a marine engine fuel, and provide insight into the initiatives and proposed research direction within MENENS.

Keywords: Internal combustion engine (ICE) · Shipping · Methanol · Alternative fuel · MENENS

1 Introduction

Using synthetic 'net-zero carbon fuels' in reciprocating internal combustion engines (ICEs) of marine vessels appears to be a promising route to decarbonize shipping [1]. Among many proposed alternative fuels, methanol is seeing an ever-increasing interest to power both existing and newbuild ships, as for instance demonstrated by the large container vessels recently ordered by Maersk fueled by green methanol [2]. Methanol's liquid state at standard temperature and pressure (STP), relatively low investment cost [3], and scalable net-zero production pathways [4] make it a promising fuel solution and a potential catalyst for the transformation to sustainable shipping.

While several combustion strategies can be employed to use methanol in ICEs, high pressure direct injection (HP-DI) of methanol appears the most

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appealing for large-bore marine engines [5], facilitating methanol's combustion in a diffusion manner. However, for smaller-bore four-stroke marine engines, the cylinder head's space constraints and cost of an extra DI system for methanol call for alternative strategies. One option is the premixed combustion mode using port fuel injection (PFI) of methanol, ignited by a spark in mono-fuel (MF) spark-ignition (SI) engines or pilot fuel in compression ignition (CI) engines. However, understanding of these technologies, particularly premixed dual-fuel (DF) CI engines with combustion modes varying from premixed to partially premixed and diffusion combustion, is still limited.

This study provides a short review of research into methanol as a marine engine fuel. First, we explore the chosen injection and ignition strategies and their resulting combustion mode across the various engine technologies. Second, we highlight some of the existing research gaps in marine ICEs fueled with methanol. Finally, we discuss the future research to be undertaken in the MENENS project to fill these gaps. This paper provides a guidance for future research on mono-fuel SI and DF CI engines and their associated combustion modes, aiming to enable methanol fuel adoption in a wider range of marine applications.

2 The Sustainable Fuel of Methanol in Shipping

2.1 Alternative Marine Fuels

Sustainable fuels can power not only the current, but also the next generation marine engines. The adoption of natural gas (NG) in marine ICEs can reduce their environmental impact, including CO_2 emissions, without abating their performance. However, NG remains a fossil fuel, thus insufficient for shipping to rely on to meet the decarbonization targets set by the International Maritime Organization (IMO). Therefore, sustainable fuels, either produced by biomass or renewable electricity, have been the central focus of recent research and development (R&D) efforts in shipping [1]. Currently, R&D mainly focus on three alternative fuels: methanol, ammonia, and hydrogen [6]. Challenges with the combustion characteristics, emissions, and toxicity of ammonia still hinder its rapid adoption in marine ICEs. Similarly, challenges with hydrogen's low energy density and wide flammability limits inhibit its potential for fast application on board of ships, especially for larger (ocean-going) vessels [7]. Consequently, methanol (see [5] for properties) continues to gain momentum for widespread use in the maritime sector, including both deep-sea and inland-shipping applications.

2.2 Sustainable ICE Operation with Methanol

Methanol's liquid state at STP and the potential for net-zero carbon engine operation using renewable methanol make it a popular sustainable shipping fuel solution [4]. Additionally, methanol has the potential to eliminate the inherent trade-off between nitrogen oxide (NOx) and soot emissions in marine diesel engines due to its high latent heat of evaporation and the absence of carbon-to-carbon molecules [5]. Lastly, the sulfur-free nature of methanol relieves ICE operations from sulfur oxide (SOx) emissions, rendering the need for scrubbers unnecessary. These benefits have placed methanol at the forefront of (R&D) efforts in shipping.

3 Methanol Trajectory in Marine Engine Applications

The long use of methanol as an ICE fuel in automotive applications and the potential of large-scale production of green methanol has drawn great attention from the maritime industry since the last decade. This has resulted in many initiatives towards the R&D of methanol-fueled engines for marine applications.

3.1 Consortium Projects

To provide a comprehensive overview of the research efforts, a chronology of previous and current research initiatives on methanol-fueled marine ICEs was compiled. Figure 1 presents the timeline of the consortium projects investigating methanol application in marine engines.

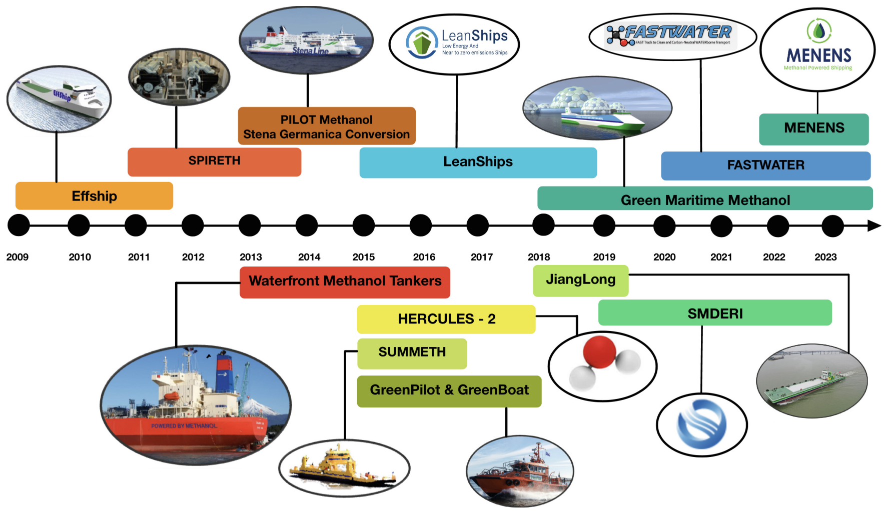

Fig. 1. Timeline of projects on methanol-fueled marine ICEs (Image courtesy MENENS project, produced using Notability.)

The Effship project initiated the efforts to explore methanol fuel [8] and the promising results derived from its evaluation resulted in the first experimental investigation of methanol in the subsequent SPIRETH project [9]. In SPIRETH, a diesel engine was converted to run on DI and diffusion combustion of both methanol and diesel, paving the way for the first on-board application in the Stena Germanica ferry where four Wärtsilä four-stroke medium-speed diesel engines were successfully converted to operate on methanol. A single dual-channel (DC) HP injector is employed to inject both fuels in the cylinder [10].

The HERCULES-2 project, where the WinGD manufacturer was involved, initiated the efforts to build efficient and environmentally friendly two-stroke engines capable of switching between different alternative fuels, including methanol [11]. Another initiative came from MAN and the Waterfront project to build seven new tanker vessels propelled by two-stroke engines powered by methanol [12]. In both two-stroke engine concepts, high pressure DI strategy was used for both diesel and methanol fuel for their subsequent diffusion combustion.

In the following years, more initiatives emerged, including the SUMMETH project focused on experimentally investigating alternative engine concepts, such as SI, to employ methanol in smaller ship applications [13]. This project also helped ScandiNAOS to build its new MD97 methanol engine employing methanol with an ignition improver to combust in the diffusive mode. Following SUMMETH, GreenPilot project was carried out to demonstrate the feasibility of converting small vessels to use methanol in SI engines [14]. In parallel, the GreenBoat project was initiated, focusing on the application of those engines in recreational crafts. The Shanghai Marine Diesel Engine Research Institute (SMDERI) also initiated its efforts to convert a commercial diesel engine to operate in diesel-methanol under diffusion combustion [15]. Table 1 provides an overview of several methanol-fueled marine engines currently available on the market. Furthermore, it is worth noting that most marine engine manufacturers have committed to introducing new methanol-fueled engines in the near future.

Table 1. Methanol-fueled marine ICEs by engine manufacturers

Engine Manufacturer	Engine Model	Type	Power range (kW)	Methanol Injection	Combustion mode	Ref.
Wärtsilä	W32 M	4x-stroke Medium Speed	3,480 - 9,280	HP-DI DC single injector	Diffusion DF	[10]
MAN	ME-LGIM	2-strokeLow-speed	4,000-60,000	HP-DI separate injector	Diffusion DF	[12]
WinGD	X-DF-M	2-strokeLow-speed	38,700-77,400	HP-DI separate injector	Diffusion DF	[11]
ABC	DZD MeOH	4-strokeHigh-speed	1,326 - 3,536	LP-PFI	Premixed DF	[16]
SMDERI	CS series	4-strokeMedium-speed	1,230 - 1,760	HP-DI separate injector	Diffusion DF	[14]
ScandiNAOS	MD97	4-strokeHigh-speed	150 - 450	HP-DI ignition improver	Diffusion MF	[17]

The LeanShips project was established to showcase methanol's potential as an ideal retrofitting choice, opting for the low-pressure (LP) PFI strategy operating the engine under the premixed combustion of methanol-air ignited by pilot diesel [18]. Following LeanShips' research output, the ongoing FASTWATER project was launched, where engine manufacturer Anglo Belgian Corporation (ABC) is also involved, to establish the feasibility of both converted and new-build vessels to run on methanol fuel [19]. The premixed DF combustion concept was also explored in a converted diesel engine in a project led by Jianglong and other knowledge institutions [20]. In the Green Maritime Methanol project, alternative strategies to use methanol in marine engines, such as a heavy-duty (HD) SI engine and a CI engine with diesel-methanol blends, were studied [21,22].

4 Research Challenges and Contributions Within MENENS

In continuation of these research efforts, the MENENS project, a Dutch consortium initiative, was established with a focus on accelerating the energy transition in shipping by developing methanol-based solutions. One of the objectives of the project is to better understand, further develop and demonstrate potential ICE technologies that can employ methanol as a marine fuel [23].

4.1 ICE Combustion Strategies and Experimental Research

In DF CI engines, there are primarily two ways for methanol combustion: premixing it with air and ignite it with pilot diesel in a process reminiscent of the Otto cycle, or combusting both methanol and diesel in a diffusive mode. The diffusion combustion approach is currently popular in methanol marine engines, especially large-bore low-speed ones. The premixed combustion concept is better suited for smaller marine engines with cylinder head constraints. However, combustion challenges, such as knocking at high loads and misfire at low loads, restrict maximum attainable Methanol Energy Fraction (MEF). Options to overcome such challenges and increase maximum MEF remain relatively unexplored, thus calling for further research into premixed DF CI engines. Further, alternative premixed MF strategies, such as using methanol in HD SI engines, can be more suitable for certain marine applications considering the trade-off between performance and emissions.

Based on the remaining challenges, one of the objectives of the MENENS project is to further explore the potential of premixed combustion concepts of methanol for marine engine applications. Exploring the capabilities of a MF methanol strategy in HD SI engines is imperative. Furthermore, we seek to draw conclusions regarding premixed combustion variances related to the methods of combustion initiation, whether it be pilot fuel flame or spark. These insights can also guide our optimization efforts for the premixed DF CI engine, potentially accelerating the sustainable transformation of the current fleet operated by the diesel engine. For this reason, two marine engines, a medium-speed CI and a high-speed SI engine, will be converted to operate on PFI methanol in the coming year. The HD SI engine and its main characteristics are shown in Fig. 2 and Table 2, respectively, located in the Appendix A.

5 Conclusions

Methanol fuel can power both existing and next-generation marine engines. However, challenges such as maximum attainable MEF and combustion stability in premixed DF engines limit its broader adoption. Using methanol in HD SI engines remains understudied, including emission characteristics for such premixed combustion concepts. To this end, research gaps have been identified within MENENS, leading to the goal of further understanding and developing premixed combustion concepts with high MEF for enabling the adoption of sustainably produced methanol in medium- to high-speed engines in the marine industry.

A Appendix - Experimental Setup

Fig. 2. The HD Marine four-stroke SI engine experimental setup in Den Helder, Netherlands (Image courtesy MENENS project.)

Table 2. Characteristics of the HD Marine SI engine

Parameter	Value	Unit
Number of Cylinders	8	-
Bore	170	mm
Stroke	190	mm
Geometric Compression Ratio	12:1	-
Rated Speed	1500	rpm
Rated Power	500	kWe

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The Ammonia2-4 EU-Funded Project: Demonstrating a 2- Stroke and 4-stroke Large Scale Ammonia Marine Engine

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Abstract. Internal combustion engines running on ammonia are increasingly considered as important facilitator among research, industry and policy communities in reaching EU environmental goals. The overall aim of the Ammonia2–4 project is to demonstrate at full scale two types of dual fuel marine engines running on ammonia as main fuel: a 4-stroke engine and a 2-stroke medium-pressure ammonia fuel injection platform. Both engine innovations are expected to result in at least 80% less GHG emissions (including nitrous oxide emissions), NOx emissions below IMO Tier III regulations and a negligible ammonia slip below 10ppm (Euro 6 compliant). The project will go beyond purely technological developments and investigate a number of non-technical aspects crucial for a successful uptake of ammonia as marine fuel: health & safety, ammonia supply infrastructure, crew training, novel standardization pathways for measurement and reporting emissions from ammonia marine engines.

Keyword: Waterborne transport

1 Introduction

Maritime transport is responsible for almost 90% of the EU's external freight trade and one third of intra-EU exchanges in terms of ton-kilometres [1]. In this context deep sea shipping has always been an important contributor. The projected growth of the global fleet in the years to come will constitute a great opportunity and at the same time a big challenge for deep sea shipping [2]. Despite the clear direct economic benefits, risks for indirect effects on environment might be at place. According to 2020 IMO data, by 2050 global GHG emissions from shipping may increase by up to 50% as compared to 2018, in case nothing changes [3]. In addition, the European Union has even more ambitious goal of cutting all transport emissions by 90% by 2050, as stipulated in the Green Deal [4].

The average age of a vessel today is 21 years according to the EU Waterborne Transport Technology Platform [5]. It becomes then clear that a large part of the global shipping fleet will be replaced by newbuilds before 2030. This is the chance the industry needs to take for "deep decarbonization" solutions.

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There is growing agreement among researchers, industry stakeholders and policy-makers that internal combustion engines (ICE) running on ammonia can be an im-

portant enabler in reaching the 2050 goals. The latest calculations published as part of DNV's *Maritime Forecast to 2050* suggest that ammonia ICEs could constitute as much as 30–80% of the total energy use by shipping in 2050 [6]. However, in order to make a real-world impact, these solutions need to be developed now and enter the market in the next 7–10 years.

2 Ammonia2–4 Objectives

The overall aim of the Ammonia2–4 project is to demonstrate at full scale two types of dual fuel marine engines running on ammonia as main fuel: a) a 4-stroke newbuild engine, demonstrated in lab conditions closely mimicking real-life operations in ambient conditions; b) a 2-stroke medium-pressure ammonia fuel injection platform, for retrofitting on existing 2-stroke marine engines; this solution will be demonstrated in two stages: a lab demonstration followed by retrofitting onto a real vessel of the alpha customer MSC.

Both engine innovations are expected to result in at least 80% less GHG emissions (including nitrous oxide emissions), NOx emissions below IMO Tier III regulations and a negligible ammonia slip below 10ppm (Euro 6 compliant).

The expected end result is the commercial exploitation within the next ten years of the demonstrated solutions towards more than 90% of the maritime intercontinental transport in terms of gross tonnage, including retrofits and newbuilds, together with an annual reduction of CO2 emitted by deep sea vessels calling at EU ports by 2.3 million tons and reduce the emissions of harmful pollutants such as SOx by 15 tons annually.

The partners believe it is crucial to develop both engine types in parallel (as opposed to consecutive development), since they serve different segments of the market: the four-stroke solution is applied on both, existing and newbuild oceangoing vessels (e.g. main engine for gas carriers, general cargo and certain bulk carrier types), while the two-stroke solution is utilized on existing oceangoing vessels (e.g. container ships, tankers, bulk carriers). The total market potential as of 2028–2030 are around 400–600 bulkers/container vessels/general cargo vessels and approximately 110 gas carriers that are planned to be built between 2028 and 2035. This is explaining why it is para-mount to develop the two solutions simultaneously.

A number of non-technical aspects will be investigated during the overall duration of the project: a) health & safety; b) ammonia supply infrastructure; c) crew training & acceptance; d) novel standardisation pathways for regulating emissions from ammonia marine engines. In addition to the intrinsic technical challenges related to the development of ammonia-fueled engines, these non-technical aspects can briefly summarize the potential barriers to reaching a successful uptake of ammonia as marine fuel. Therefore addressing non-technical challenges is a must-have condition for the Ammonia2–4 solutions to win also on regulatory, heath and safety, and commercial grounds.

The driving force behind the project is a Pan-European consortium consisting of the leading marine equipment manufacturer Wärtsilä, the largest classification society worldwide, DNV, one of the world's top three container shipowners, MSC, the award-winning naval architecture SME C-Job, and the largest research institute in Italy, CNR.

The consortium will work towards closing the current technological, commercial and regulatory gap between insights on the feasibility of burning ammonia in small engines and the actual proof that a large oceangoing vessel can be powered by ammonia as the main fuel in a safe, operationally efficient and economical way.

3 State of the Art

The majority of today's deep-sea vessels rely on two types of ICEs as prime movers: two-stroke and four-stroke engines. In four-stroke engines, the entire combustion cycle is completed, and mechanical energy is produced in four piston strokes. In two-stroke marine engines, the cycle is completed in just two piston strokes, as the engine's different design enables to take advantage of both sides of the piston.

The different mechanical and physical features embedded in two- and four-stroke engines appeal to different segments of the deep-sea shipping marketspace. Shipowners operating fleets of very large vessels such as container ships or tankers typically prefer two-stroke engines due to their robustness and simpler machinery layout. In almost all cases, these ships also have one or more smaller auxiliary four-stroke engines to power on-board systems and the ship's electrical grid. Owners of general cargo vessels or gas carriers on the other hand turn to four-stroke engines as medium-to high-speed prime movers with a higher power density. Despite this, the basic physical principles behind the two-stroke and four-stroke combustion cycles remain the same and will continue to play a major role in the years to come.

The success of alternative fuel sources such as ammonia, methanol or liquid hydrogen to increase low-emission solutions in the market will depend on novel approaches towards combustion methods to maximise efficiency, safety and reliability. Emerging technological alternatives to ICEs, such as fuel cells or electric batteries, will contribute to the decarbonization of shipping, but are currently feasible only on a minority of vessels, i.e. those focusing on low power applications and/or shorter range [7]. Breakthrough ICE technologies looking at the combustion of alternative fuels such as ammonia are currently the only feasible option for enabling the decarbonization of deep sea maritime sector.

To date, ammonia has not been used as a fuel for shipping in practice. And until very recently, all laboratory experiments with ammonia as fuel centered around "engine like" equipment such as rapid compression machines and combustion bombs, but also included some small scale (car or truck size) research engines. This all changed when Ammonia2–4 project partner Wärtsilä Group conducted its first experiments on an actual multi-cylinder medium speed four-stroke marine engine in June of 2021. During these ground-breaking tests, an ammonia share of 60% (by energy content) was reached at an engine load of 75%. The EU-funded project Ammonia2–4 will build on this result developing and demonstrating the feasibility of large-scale ammonia marine engines covering both, the two-stroke and the four-stroke market segment.

4 Methodology

The Ammonia2–4 project methodology has been organized as a matrix, where the individual development steps (Specify, Develop & Validate, Demonstrate) are structured along two development tracks: one for the two-stroke ammonia fuel injection platform and one for the four-stroke newbuild ammonia engine. Additionally, a number of non-technical tasks will be complementing the technical development work to ensure the technological outputs of the project align with the regulatory and commercial framework conditions and can be exploited and commercially scaled post-project. It is important to note that the non-technical tasks have not been pushed towards project end but will accompany the entire project. Figure 1 presents the Ammonia2–4 methodology at a glance.

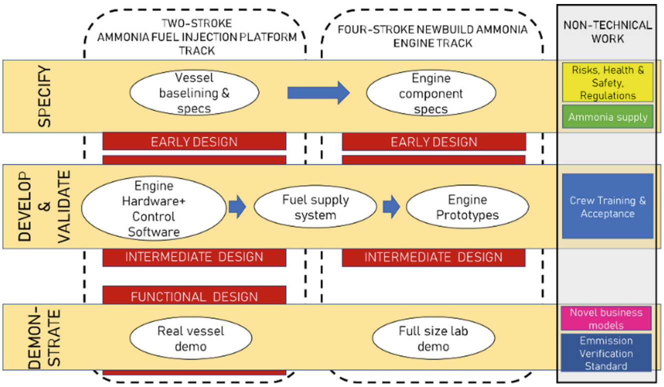

Fig. 1. Ammonia2–4 project methodology

The "Specify" Development Step

This step will begin by baselining the target vessel types in order to define the KPIs against which the project progress will be measured. Secondly, the partners will develop specifications of hardware components and control.

The "Specify" development step will also incorporate two important non-technical tasks to run in parallel to the works described above. Firstly, the partners will develop a framework for mapping (in six-month intervals) any emerging regulations in regard to ammonia handling (including environmental, health & safety). The exercise will depart from DNV's Gas fuelled ammonia classification rules published in July 2021 and the Ammonia as a Marine Fuel Safety Handbook and constantly update the framework with potentially new regulations by classification societies and flag states [8]. The second non-technical task will be a study on the ammonia supply along the main shipping routes. The study will look on the one hand into the already existing ammonia supply infrastructures and the types of ammonia (green, blue) as well as further industry and policy initiatives to make ammonia available for shipping.

The "Develop and Validate" Development Step

This step will begin with the development of hardware components for both innovations based on the specifications in the previous step. For the four-stroke engine, the development will focus on the design of fuel injection system, based on the findings of the measurements and experience from 2021. For the two-stroke engine, firstly, the hardware development will look into the re-designing of the pressure amplifiers, accumulator and injection module. Secondly, the control software will be developed, tested in silico and debugged for both innovations. Thirdly, engine performance models will be developed based on simulations and test results and fed to DNV's COSSMOS suite for modelling a vessel's efficiency. The proprietary tool of DNV enables to create digital twins of the vessel's machinery and ultimately simulate its real operational performance once equipped with the Ammonia2–4 engines. Fourthly, two intermediate designs of the engines, the fuel supply system and their integration into the two-stroke MSC container vessel and the four-stroke bulker will be created. Finally, the MSC crew will accomplish a training on the operation of the ammonia engine.

The "Demonstrate" Development Step

The third development step will be initiated by developing the functional design of the two-stroke engine (to be retrofitted into real vessel) and will inform particularly the on-vessel installation of the two-stroke ammonia injection platform.

As part of the demonstration of the four-stroke newbuild ammonia engine, Wärtsilä's R&D team will update the engine to its final specification and conduct a multi-day consistency check. Afterwards, a comprehensive 14-day dynamic testing programme to simulate real engine operation will be conducted. For the two-stroke demonstration, the ammonia fuel injection retrofit platform components will be manufactured and transported to a shipyard, where they will be retrofitted into the MSC vessel. After installation, an approval by the vessel's classification society will take place, before a 6-month demonstration voyage can be undertaken.

As environmental performance, regulatory compliance and transparency are important enabler of commercial exploitation, DNV will create and demonstrate a Recommended Practice (RP) that will set requirements on how to measure, evaluate and verify emissions across the operational profile and in real-life conditions. The proposed RP will go through DNV's hearing processes allowing relevant stakeholders to scrutinise the standard as well as ensure industry buy-in.

Finally a report on novel commercialisation strategies, including business models and novel value propositions (e.g. real-time GHG emission measurement coupled with EU MRV reporting) will be drafted, although not publicly shared.

5 Current Public Outcomes

For the time being the following two public reports have been drafted and have been shared for open access through the Zenodo platform.

First the report "**Safe working environment in laboratories dealing with ammonia**" report by Wärtsilä is building on the experience gained during the July 2021 tests and describing from one side the properties of ammonia and its effect on humans and on the environment and from the other side how to safely deal with this substance used as fuel inside the engine laboratories. In this context the report explores safety measures to be adopted during operations, maintenance and related personal protective equipment to be adopted and training to be taken in advance.

Secondly, in the "**Foresight report on future availability of green/blue ammonia in 2030, 2040 and 2050 scenarios**" DNV is conducting a forecast mapping on both green and blue ammonia availability to assess their supply needs in 2030, 2040 and 2050. The study has been based upon DNV's Maritime Forecast to 2050 publications and take into account regulatory and policy developments, cost developments within renewable energy, electrolyzers and ammonia production as well as trade growth.

6 Summary

The experience gained so far inside the Ammonia2–4 consortium is confirming that the use of ammonia as fuel in internal combustion engines is a viable option when it comes to reducing GHG emissions in the atmosphere. Although these promising early results, the Ammonia2–4 consortium will keep working in order to close the existing gaps in terms of ammonia fuel efficiency, health and safety issues, environmental concerns and regulatory aspects, at the same time laying the foundations for a smooth and rewarding commercial exploitation.

7 Disclaimer

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Practical Approach Towards Green Methanol as Maritime Propellant

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Abstract. Maritime transport plays an essential role in the EU economy and is one of the most energy-efficient modes of transport. Nevertheless, it is as well a large and growing source of greenhouse gas emissions. Consequently, the use of alternative carbon-neutral propellants in shipping must be investigated and promoted.

Green methanol is a promising candidate as a future maritime propellant, which is currently investigated in the scope of the research project MariSynFuel funded by the German Federal Ministry for Digital and Transport. At the project's core is the development and construction of a facility for manufacturing green methanol on a demonstration scale in Bremerhaven, Germany, and the direct use of the fuel for the newly-built research ship 'Uthörn' of the Alfred Wegener Institute. The vessel, christened in November 2022, is equipped with two diesel engines retrofitted for methanol combustion. Because methanol has favourable storage and transport characteristics, it has numerous advantages in terms of storage and handling compared to pure hydrogen or ammonia. It is also biodegradable, which is important in the event of accidents at sea or in ports. In addition, existing tank farms and tank transporters can be converted with little effort and continued to be used.

The planned demonstration facility is to produce at least 500 kg of green methanol per day, matching the expected daily consumption of the 'Uthörn'. To ensure the operation of the methanol synthesis facility and the acceptance of the manufactured methanol, a supply and distribution concept is developed within the project, which together with the preparation of a business plan will facilitate an economic perspective of the project's approach. The generation and marketing of synthetic fuels at Bremerhaven is a first, essential step towards a more sustainable, local maritime energy supply and contributes to becoming less dependent on the import of fossil energy sources in future as well. The presentation will provide insights into the project and highlight first project results.

Keywords: Green Methanol · Synthetic Fuels · Shipping · Maritime Propellant · Methanol Combustion

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1 Introduction

In today's EU economy, which substancially relies on globalized goods flows, maritime transport and especially deep-sea shipping play an essential role. On the one hand side, deep sea shipping currently is one of the most energy-efficient modes of transport, as shipping remains the lowest emission form of transport per travelled distance [9], but nevertheless, on the other hand side, it is as well a large and growing source of greenhouse gas emissions. According to the European Environment Agency, maritime transport causes about three percent of the European Union's total CO_2 emissions, as an example, in 2019 more than 144 million tons of CO_2. As deep-sea shipping has been one of the fastest growing sources of greenhouse gas emissions for many years, shipbuilders and vessel operators are investigating environmentally friendly alternatives to conventional fossil maritime propellants like heavy oil or diesel fuel [1].

In order to achieve the desired climate neutrality and to create a defossilized economy, Germany needs sufficient hydrogen imports. According to the German National Hydrogen Strategy, imports of at least 45 TWh of hydrogen per year will be required from 2030 on. In addition to pipeline imports, hydrogen carriers can also be imported by ship. There is consensus that liquid molecules such as Fischer-Tropsch products or methanol can play a significant role for energy imports to Germany because their transport is comparatively easy; they as well offer the possibility of direct use instead of cracking [2]. With regard to deep-sea shipping, the investigation and promotion of alternative carbon-neutral propellants in shipping thus are of vital importance [3].

According to the current state of knowledge, renewable hydrocarbons are the most feasible option for the defossilisation of international deep-sea shipping. As green shipping fuel, synthetic green methanol (e-methanol) is in discussion, besides synthetic diesel fuel and SLNG [2]. Another potential candidate is green ammonia.

This paper elaborates the potential advantages and disadvantages of e-methanol as a marine propellant. The investigations are conducted within the German national research project MariSynFuel. At the project's core is the development and construction of a facility for producing green methanol on a demonstration scale in Bremerhaven, Germany, and the direct use of the fuel for the research ship 'Uthörn' of the Alfred Wegener Institute. The vessel, christened in November 2022, is equipped with two diesel engines retrofitted for methanol combustion. The intention of this paper is to introduce the MariSynFuel project to the research community on European scale and to provide first insights into the project and first related outcomes.

2 Green Methanol as a Shipping Propellant

Before the year 2020, methanol was considered a fuel option for methanol tankers only. First orders for methanol-fuelled containerships were placed in 2021, which resulted in considerable interest in methanol as a shipping propellant across all ship segments [3]. The main advantages of green methanol are the known technologies and the existing market and related infrastructure, which were built in the past for conventional methanol based on fossil raw materials [4]. In addition, existing facilities currently used for conventional fossil fuels like tank farms and tank transporters can easily be converted to supply methanol with little effort and continued to be used [3]. Nevertheless, methanol bunker facilities currently are not yet developed for deep-sea shipping. Bunkering to date is available only by truck or small bunker ships, thus more sophisticated means of bunkering need to be developed. According to the Green Maritime Methanol project, methanol bunker fuel through specific safety measures can be designed into a tolerable safety risk region, providing a safety level which is comparable to conventional fossil marine fuels [10]. Main engine and generator technology for methanol is available, built and in operation. More engine types are currently under development [3].

Compared to other defossilized energy carriers like, for example, pure hydrogen or ammonia, methanol has favourable storage and transport characteristics. In particular, cooled or compressed storage is not necessary, and, unlike ammonia, methanol is by far less toxic. In addition, methanol is easily biodegradable, which is important in the event of accidents [11]. Consequently, the handling of methanol implies significantly lowered requirements in comparison to competing alternative energy carriers. In comparison to liquid or compressed hydrogen, green methanol has a significantly higher energy density and thus is particularly advantageous for long-distance transport and long-term storage of renewable energy [4]. Consequently, it can be used without significantly displacing the load capacity of cargo vessels, unlike other alternative fuels [9]. Another central advantage of methanol is that significantly less pollutants are released into the air during combustion. Methanol produces 99% less SO_X, 95% less PM, and up to 80% less NO_x than marine gas oil (MGO) [8].

If the utilized methanol is synthesized from CO_2 stemming from sustainable sources and “green” hydrogen produced with renewable energy, this fuel is particularly sustainable and climate-neutral and thus can be referred to as “green” methanol. In that way, green synthetic methanol can provide considerable reductions in greenhose gas (GHG) and air pollutant emissions. The technology for the green production of methanol is available today, nevertheless currently for production of small volumes only [3]. In general, green synthetic methanol is expected to play an important role in the fuel mix of the future. Its future share in particular in the maritime sector is dependent on several factors, such as the upscaling of green methanol production, the costs of green methanol, and the acceptance of ammonia as a competing maritime propellant [5].

3 Sources of Green Methanol

In order to assess the feasibility of the introduction of green methanol as a maritime propellant on a global scale, it must be investigated if the necessary volumes of green methanol can be produced under reasonable boundary conditions in the coming years. According to the Methanol Institute, methanol is already today widely available and easy to source. Methanol production capacity is expected to expand significantly by 2050, reaching 500 million tons, 80% of which is expected to be synthetic green methanol and bio-methanol [8].

Hank et al. analyzed suitable Power-to-X pathways in developing and emerging countries, in particular the generation and export of five different PtX products (liquid and gaseous hydrogen, ammonia, methanol, jet fuel) in twelve countries [6]. Ten of the twelve countries were considered for the export of green methanol. The analysed countries were Algeria, Australia, Colombia, India, Mexico, Morocco, Namibia, South Africa, Spain, and Tunisia. The results are shown in Table 1, including the costs for methanol production as well as its transport via ship to Germany. Within these countries, 34 regions were considered in particular.

Table 1. Levelized supply cost of green methanol including transport to Germany via ship [6].

Country	Levelized cost of methanol
Algeria	202 – 222 €/MWh
Australia	192 – 200 €/MWh
Colombia	190 – 274 €/MWh
India	232 – 264 €/MWh
Mexico	237 – 244 €/MWh
Morocco	225 – 247 €/MWh
Namibia	222 – 240 €/MWh
South Africa	226 – 236 €/MWh
Spain	216 – 230 €/MWh
Tunisia	214 – 224 €/MWh

In the comparison of the analyzed countries for production and supply of green methanol based on carbon dioxide captured from the atmosphere, Colombia, Australia and Algeria have the lowest production costs, followed by Tunisia and Spain. In particular, the Colombian region La Guajira has the lowest supply cost of 190 €/MWh, which equals to 1052 EUR/ton green methanol. The overall range of supply costs assessed during the analysis is from 190 €/MWh until 274 €/MWh and thus implies considerable deviation, caused by individual circumstances in the analyzed regions.

In this paper, we would like to highlight the case of Australia, which possesses tremendous land potential. All Australian regions which were included in the study show low production costs for green methanol and offer cost-efficient large-scale ship transport to Germany. In addition, the country has a well-established political stability, together with excellently developed infrastructures, high education standards, and availability of the necessary workforce [7]. Thus, Australia offers excellent conditions for the production of renewable energy. The fact that the transport distance between Australia and Germany is considerably longer compared to any other export country, which previous studies considered a severe shortcoming, in the new study turned out to be of minor relevance, not interfering with the otherwise positive evaluation [6].

In case of European export countries for green methanol, only Spain was included in the study, scoring above average compared to the other assessed countries. In particular, the two regions of Pedrola and Gibraltar show promising potentials for the production of green methanol [6]. Nevertheless, we conclude that it is necessary to investigate other European export regions such as e.g. Iceland, Norway, Scotland, and the UK as well, in order to achieve a reliable and well-founded assessment of green methanol production conditions in Europe. Results from the MariSynFuel project, especially on the costs and the boundary conditions of domestic production of green methanol in Germany, will be included in future studies as well.

As a conclusion, the cited study indicates that green methanol can be produced and supplied from a considerable number of export countries and regions at reasonable costs, thus facilitating a large-scale uptake of green methanol as a maritime propellant in a medium-scale timeframe. The authors emphasize that when assessing the costs of green energy carriers, it is imperative to consider the current price developments of conventional fossil fuels and include the resulting environmental costs in the calculations, such as environmental hazards unavoidably linked to a fossil economy [6].

4 The MariSynFuel Project

The MariSynFuel project started in January 2023. Its overall goal is to develop a technology for the production of synthetic green methanol as a propellant for shipping in Bremerhaven. The project is coordinated by the Technology Transfer Center (ttz) Bremerhaven. Project partners are the Alfred Wegener Institute and the Institute of Shipping Economics and Logistics, together with the companies UTG Unabhängige Tanklogistik GmbH, Green Fuels GmbH and the shipping company F. Laeisz.

The core of the project is the development and construction of a plant for synthetic green methanol production on a demonstration scale in Bremerhaven and the direct use of the fuel as a propellant for the Alfred Wegener Institute's new research vessel 'Uthörn', which is equipped with two diesel engines that have been converted to methanol combustion, which in turn generate electrical energy for the vessel's electric propulsion. It is the first German seagoing vessel to be equipped with an environmentally friendly methanol-based propulsion. The planned production facility will at its final stage of development produce at least 500 kg of green methanol per day, matching the expected daily consumption of the 'Uthörn'.

To ensure a successful implementation of the methanol production facility, it will be developed in three stages. First, a pilot plant with a production capacity of 1–2 kg/d will be set up, which is used to test and optimize process parameters and catalysts. In the second step, an optimized reactor with an improved design and an expanded production capacity of 5–10 kg/d will be developed, which will already possesses the final reactor design as well as optimized process parameters. In the third step, the scale-up to the final production capacity takes place. The plant development is carried out in the mentioned steps in order to identify the relevant process parameters for the scale-up, which must be adhered to with regard to an optimal production process of green methanol.

To ensure the operation of the methanol synthesis facility and the acceptance of the produced methanol, a supply and distribution concept will be developed within the project, which together with the preparation of a business plan will facilitate an economic perspective of the project's approach. The MariSynFuel project will thus serve as a lighthouse project in Bremerhaven, being the second largest seaport in Germany, and support the expansion and market ramp-up of the technology. Consequently, the production and marketing of synthetic fuels at Bremerhaven is a first, essential step towards a sustainable, local maritime energy supply and contributes to becoming less dependent on the import of fossil energy sources as well. Nevertheless, as pointed out before, we expect that Germany will never achieve a complete independency from foreign export countries. Thus we expect that green methanol both from domestic sources and from exporting countries will play a role with regard to maritime energy supplies. The principles of economic co-existence will be investigated in MariSynFuel as well.

5 Conclusions

The demand for synthetic fuels will increase in the coming years, in particular in seaports, since we expect that more and more seagoing vessels will be equipped with respective propulsion. Especially green methanol has large potentials to play a major role in the defossilization of maritime transport. This paper introduces the German national project MariSynFuel to the scientific audience, which aims to establish a production line of green methanol in Bremerhaven, Germany. Economic co-existence of domestic production and imports will be investigated as well. There is a general transferability to other ports with similar areas of application and infrastructural conditions.

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Investigation into Condensation for Various Fin Shapes for Condenser Design in a Water-Enhanced Turbofan (WET) Engine

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Abstract. The Clean Aviation Sustainable Water-Injecting Turbofan Comprising Hybrid-Electrics (SWITCH) project aims to answer the challenge of climate-neutral Small to Medium Range (SMR) transport by developing a revolutionarily sustainable gas turbine propulsion system and further boosting it with hybridization to improve energy efficiency by 25% and reduce non-CO_2 related climate impact by more than 60%. The core of SWITCH is the revolutionary Water-Enhanced Turbofan (WET) concept, which offers unmatched potential to enable climate-neutral aviation based on existing and future infrastructure, while also retaining the key benefits of gas turbine propulsion to meet the full range of thrust, speed, and all other mission requirements. Wet combustion allows NOx emission reduction of more than 80% and water recovery traps particles resulting in cleaner exhaust. One of the technologies being developed by Collins Aerospace is a condenser for the WET engine. To have a high efficiency and compact condenser, a range of plate-fin geometries are being explored to provide high surface area to volume ratios and low hydrodynamic resistance. This will ensure the design targets of size, weight, overall heat transfer and pressure drop are met. High fidelity and multi-physics models coupling of fluid dynamic, heat transfer and phase change will be included in condenser design tool with consideration of condensation effects on heat transfer performance. The developed models are validated against measurements from testing, such as measured heat transfer coefficient and pressure loss. This paper will present an overview of the condenser design tool and latest results.

Keywords: Condenser · Gas turbine · Water Injecting Turbofan

1 Introduction

Sustainable Water-Injecting Turbofan Comprising Hybrid-Electrics (SWITCH) is part of Clean Aviation Joint Undertaking, which aims to transform aviation towards sustainable and climate-neutral future. The core of SWITCH is the Water Enhanced Turbofan engine concept which can be explained using Fig. 1. Unlike a conventional gas turbine cycle operating in aircraft, WET engine has a dual-fluid cycle which are air and water. It is

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evident from Fig. 1 that the WET engine has the same structure as that of a conventional gas turbine engine to the exit of compressor. However, superheated steam is injected into the combustion chamber in addition to fuel to induce wet combustion. Subsequently, the mixture expands inside the turbine to produce mechanical power and then cooled in a steam generator. Eventually, the water in the mixture is extracted employing a condenser and the collected water is added back into the cycle. Thermodynamics analyses indicate that high heat carrying capacity of steam-air mixture increases work output of the turbine and reduces the work required by the compressor [1].

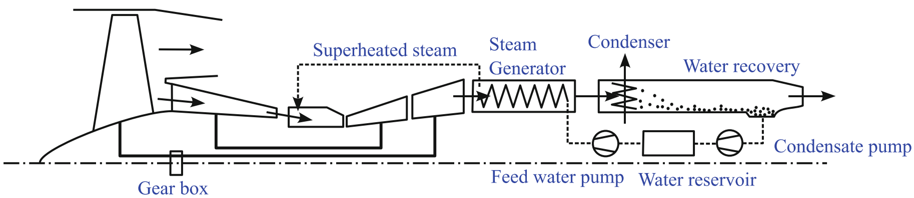

Fig. 1. Water Enhanced Turbofan concept [1]

It is self-evident that there will be a limitation to the amount of water which can be carried onboard in an aircraft powered by the WET engine. Therefore, recovering the water which is injected in the form superheated steam into the combustion chamber is crucial, which signifies the importance of a well-designed condenser in the engine. Here, the condenser is fundamentally a heat exchanger whose hot-side is the exhaust gases from the turbine and the cold-side is the bypass air of the engine. Hot side gases need to be cooled the pressure-dependent dew-point temperature to initiate condensation inside the heat exchanger. While the design methodologies for single-phase, compact, plate-fin heat exchangers are well-developed, issues such as the effect of condensation on the heat exchanger design, effect of non-condensation gases, impact of various orientations of the heat exchangers on water recovery, presence of particulates in the hot-side flow and more needs to be carefully studied.

The studies on the condensation of steam in the presence of non-condensable gases are not new. Such a problem was theoretically solved without any empirical data and theoretical predictions were compared against experimental data [2]. Furthermore, analytical investigation of laminar film condensation of steam over a vertical plate with air as the non-condensable gas was evaluated and demonstrated that even small amount of non-condensation gas has decisive effects of the heat transfer rates [3]. Later, it was also found out that the impact of non-condensation gases on the heat transfer rates were more significant at low operating pressures in a forced convection condensation problem [4]. These investigations were also carried out with Helium as a non-condensable gas instead of air [5–7]. However, as there are several factors that influence the condensation phenomenon in a duct, modelling using Computational Fluid Dynamics tools became convenient in many studies [8–10]. Moreover, there are few researches which specifically study and set guidelines for the design and modelling of compact condensers inside aeroengines. The present study aims to conduct CFD simulations on condensation and validate them using literature. It is also targeted to construct and validate a low-fidelity design code which can do the sizing and performance calculations of a plate fin heat exchanger for single phase flows. Results from the design code are compared against those in the literature. Eventually, the low fidelity heat exchanger design too will be upgraded to encompass effects of phase change heat transfer as well in the performance and sizing calculations.

2 CFD Simulations

A set of steam condensation experiments were conducted by Kuhn et al. [7] and were numerically simulated by Jun-De Li [8]. In the experiments, condensation occurs in a vertical steel tube where steam and air mixture were passed vertically downwards while steel tube was cooled by an annular jacket around it in which water was passed vertically upwards. Temperature profiles along the length of the condenser tube were reported. In this study, we employed the above-mentioned literature to validate the CFD simulations. A commercial, finite-volume solver was used to solve the film condensation problem. The computational domain was constructed according to dimensions prescribed by the literature and a fully structured mesh was constructed. The boundary conditions were the same as that of the test case 2.1-8R in the literature. Inlets were considered known-mass flow inlets and outlets set as known-pressure outlets.

The simulations were transient, turbulent, and three-dimensional in nature. The steam-air mixture was assumed a multi-component, ideal, and non-reacting gas mixture while water and steel were considered have constant density. The mode of condensation is assumed to film-wise condensation and fluid-film model was used to solve the condensation. In order to use the model, a shell interface of single cell thickness was created at the solid-fluid interface, where condensate film was expected to form and additional continuity, momentum, energy and species conservation equations were solved for the fluid film. In general, the model is capable of handling multiple gas species and their interactions with their respective condensate film formed at the interface. It should be noted that gravity was always turned on during the simulations which is inevitable in multiphase simulations. Furthermore, multiple timescales were utilized in the present study as the condensation heat transfer at the fluid-solid interface needed at low time-step (0.0001 s) whereas the heat conduction through steel could have large time-step (0.2 s). The thickness of the fluid film, and the temperature profiles were monitored during the calculations and the convergence was identified when the maximum fluid film thickness remained unaltered for thousand-time steps. Nevertheless, it is conventional to evaluate the residuals of mass, momentum, energy, species, and turbulence which were estimated to be below 10^{-5}.

3 Low-fidelity Condenser Design Tool

While three-dimensional computational simulations are precise and can provide comprehensive results, they are often time-consuming when it involves multiphase physics and geometrical optimization. Therefore, to have the initial design and performance estimation of the condenser, a low-fidelity design tool is employed. Nevertheless, phase change effects are ignored in the initial versions of the design tool. The well-known, Epsilon-Number of Transfer Units (NTU) method is employed to calculate the performance of heat exchanger [11] and is written in MATLAB language.

Figure 2 shows how the design tool works. There are three types of input files: the geometrical details and constraints are given by architecture setup file (.txt) and case configuration file (.txt) whereas the boundary conditions are given by operating point file (.csv). Design tool operates either in the design or performance modes which respectively represent the sizing and rating calculations for a heat exchanger. In the performance mode, the geometrical features, such as the length of heat exchanger and fin width or fin height, remain fixed. The results of a performance calculation are the overall thermal and fluid flow performance like the heat transfer rate and pressure drops on either side. In the design mode of the tool, the upper and lower bounds of the geometrical features along with constraints are provided to minimize the objective functions, which is the mass of the heat exchanger core. The constraints generally are the requirement for pressure drops and overall heat transfer rate of the heat exchanger. In the present study two performance calculations are presented to validate the methods used in the design tool. One of which are taken from Shah et al. [11] and deals with the performance calculations of a heat exchanger with offset-strip fin. The latter is based on experimental data from Collins Aerospace and studies a wavy fin.

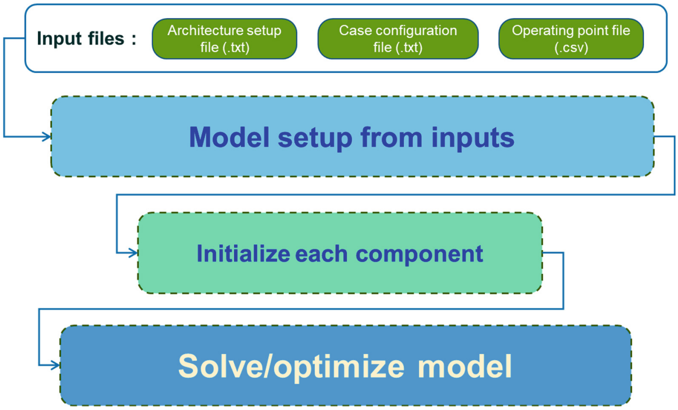

Fig. 2. Approach employed in the Design tool

4 Results and Summary

The comparison of adiabatic wall temperature among the simulations performed in the present study, the same in the literature and those from experiments reported in the literature is shown in Fig. 3. It can be seen the numerical methods utilized in the present study could predict the numerical and experimental results in the literature reasonably well. The maximum deviation was found to be close to the exit of cooling water and could be due the omittance of buoyancy effects of water at the exit. Furthermore, the maximum thickness of fluid film was estimated to be 0.118 mm.

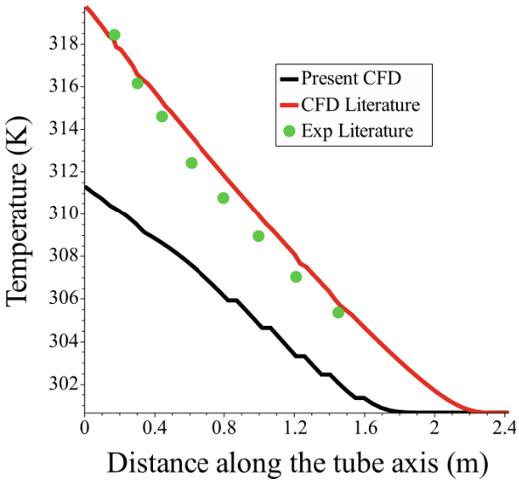

Fig. 3. Comparison of adiabatic wall temperature

Table 1 shows the performance calculations of an air-to-air heat exchanger, adopted from Shah et al. [11] and how the design tool was able to predict the results. The plate-fin heat exchanger had offset-strip fins on the hot and cold sides and the overall dimensions were 0.3 m × 0.3 m × 1 m. According to Shah et al. [11], the heat exchanger could offer a heat transfer duty of 1.08 MW with 83.11% effectiveness while the design tool predicted 1.07 MW of heat transfer duty with 83.09% effectiveness. The NTUs suggested by Shah et al. [11] and the design tool were respectively 6.97 and 7.21. The comparison of the Reynolds number, f and j factors, heat transfer coefficients, pressure drop, and outlet temperature on either side of the heat exchanger, given by Table 1 proves that the methods used in the design tool in the present study are excellent.

Table 1. Comparison of results from design tool and Shah et al. [11]

	Hot side		Cold side	
	Shah et al. [11]	Design tool	Shah et al. [11]	Design tool
Reynolds number	589	628	842	864
Colburn factor	0.017	0.017	0.0134	0.0149
Heat transfer coefficient (W/m^2K)	360.83	366.67	336.81	358.96
Heat capacity (W/K)	1863	1845	2146	2163.4
Outlet temperature (deg. C)	318.3	318.35	705	696
Friction factor	0.0622	0.0668	0.0593	0.0572
Pressure drop (Pa)	9031	9343	8394	8271.4

Additional validation of the methods employed in the design tool was performed by performing another validation study in which a heat exchanger's performance was compared against experiment conducted in Collins Aerospace. The heat exchanger was air to air, plate-fin heat exchanger with wavy fins on the hot and cold sides. Like it was done in the first validation study, the performance prediction from the tool were compared against those from the experiment and the percentage differences were recorded. Only −0.34% difference was found in the heat transfer duty and 1.1% difference was found in the effectiveness. Furthermore, the comparison of the Reynolds number, f and j factors, heat transfer coefficients, pressure drop, and outlet temperature are shown in Table 2 as the percentage differences. The small differences between the predictions from the design tool and the experimental data once again prove that the methodology described in the design tool are well built and can be used for basic rating and sizing calculations of compact plate-fin heat exchangers.

Though the CFD and low-fidelity methodologies are well-validated, parametric studies of condensation inside the fin shapes need to be completed. It is crucial to know how much condensate will be formed at different operating conditions and fin shapes. Eventually, the fin characterization at various conditions will help to simplify the modelling of the heat exchanger/condenser. Furthermore, the inclusion of the effects of condensation on the rating and sizing calculations of the heat exchanger design tool needs to be carried out. All the aforementioned aspects will be carried out in the later stages of the research.

Table 2. Comparison of results from the design tool and experiment

	Percentage difference between tool and experiment	
	Hot side	Cold side
Reynolds number	−2.6	−5.4
Colburn factor	2.1	3.2
Heat capacity (W/K)	−1.5	−1.3
Outlet temperature (deg. C)	−1.8	0.7
Friction factor	4.9	5.5
Pressure drop (Pa)	4.0	−1.4

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Author Index

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