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Research paper

Comparative life cycle assessment of district heating supply pathways: Insights from waste heat and CHP configurations

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ABSTRACT

Decarbonising heat is a critical challenge for achieving climate goals, as heating accounts for around 40 % of global energy demand and nearly 30 % of global greenhouse gas (GHG) emissions. District heating (DH) systems provide a scalable, low-carbon alternative to decentralised heating; however, their Life Cycle Assessment (LCA), particularly when integrating renewable supply options, remains underexplored in the literature, especially for emerging markets such as Ireland. This study introduces a novel integrated LCA framework that captures both embodied and operational carbon emissions of alternative DH supply configurations. The framework combines SimaPro for life cycle inventory with HOMER Pro for techno-economic modelling and includes sensitivity analysis of critical parameters. Three scenarios were assessed: a waste-heat-fed DH system, a natural gas combined heat and power (CHP) system, and a biogas CHP system. The results show that the waste heat-fed system exhibits the highest embodied emissions (402,000 kg CO_2eq) compared with 256,000 kg CO_2eq for the biogas CHP. In terms of operation, the biogas CHP system achieves up to a 72.9 % reduction in annual GHG emissions relative to natural gas CHP. Over a 20-year lifetime, the biogas CHP achieves the lowest overall life cycle carbon footprint per functional unit, compared with natural gas CHP. These findings highlight the value of integrating life cycle carbon assessment into DH system evaluation and provide practical insights for policy and infrastructure planning to accelerate the decarbonisation of heating.

1. Introduction

The global reliance on heat, which represents the largest portion of energy end use worldwide [1], is deeply tied to environmental concerns due to its heavy dependence on fossil fuels. This sector alone is responsible for 40 % of global CO_2 emissions, contributing significantly to climate change [2]. In the EU, space and water heating in buildings make up 28 % of energy consumption, with the majority, 70 %, of this energy still coming from fossil fuel sources [3]. The global energy landscape is transforming, shifting from reliance on fossil fuels to an increased adoption of renewable energy sources [4]. In response to the negative impacts of heat-related activities, the European Green Deal has set goals to reduce greenhouse gas (GHG) emissions by at least 55 % by 2030, compared to 1990 levels [5]. In Ireland, electrical demand is shadowed by the heat and transport sectors, as shown in Fig. 1 [6]. Therefore, therefore it is important to investigate its decarbonisation. Ireland is currently the lowest in Europe for renewable energy use in heating and cooling, at 6 % in 2022 [7]. As a result, it faces a huge challenge in decarbonising the heating sector.

The best-performing countries for renewable heating typically have a high share of efficient DH systems that supply both homes and businesses. DH is a proven technology that is widely used across Europe, supplying two-thirds of Denmark's heat and over 90 % of heat demand in sustainable cities like Copenhagen and Stockholm [8]. The EU has established a robust policy framework promoting DH via the Energy Efficiency Directive [9], and Renewable Energy Directive [10]. These directives emphasize DH's role in energy efficiency, renewable integration, waste heat recovery, and regulatory harmonisation with electricity sectors.

DH is a centralised system that distributes heat as hot water or steam from a central source to multiple buildings, improving energy efficiency and reducing emissions compared to individual heating systems [8]. DH systems can utilise various heat sources, including biomass, heat pumps, solar energy, and waste heat [4]. While traditional DH systems often rely on fossil fuels, there is significant potential for decarbonization by

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Nomenclature

E-LCA	Environmental Life Cycle Assessment
DH	District Heating
GWP	Global Warming Potential
CHP	Combined Heat and Power
TDHS	Tallaght District Heating Scheme
FU	Functional Unit
IrDEA	The Irish District Energy Association
LCA	Life Cycle Assessment
CAP	Climate Action Plan
LCI	The Life Cycle Inventory
SSRH	Support Scheme for Renewable Heat
RED	Renewable Energy Directive
AD	Anaerobic Digestion
EED	Energy Efficiency Directive
LCIA	Life Cycle Impact Assessment
PEF	Product Environmental Footprint
OEF	Organisation Environmental Footprint
ECB	European Central Bank
NCV	Net Calorific Value
TLC	Thermal Load Controller
CO	Carbon Monoxide
UHC	Unburned Hydrocarbon
NOx	Nitrogen Oxides
SEAI	Sustainable Energy Authority Of Ireland's

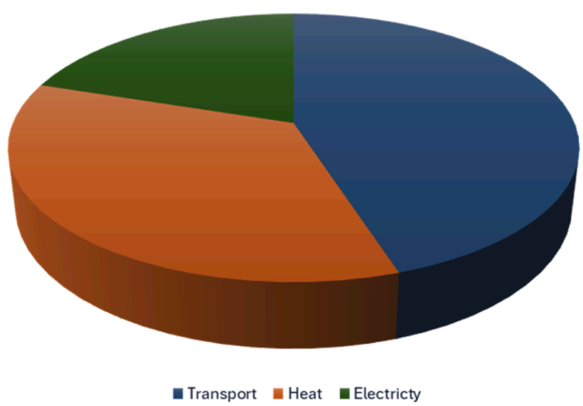

Fig. 1. Percentage share of energy in transportation, heat and electricity sectors 2023 [7].

integrating renewable energy sources [11]. DH systems are typically more efficient and environmentally friendly than decentralised heating options, making them cost-effective and sustainable solutions [12]. Many DH networks worldwide, including Rotterdam's, rely on fossil fuels such as natural gas or coal for heating [13]. These systems are simpler and less costly but are less efficient and contribute significantly to greenhouse gas emissions compared to decarbonised alternatives [14, 15]. Recent and novel approaches apply machine learning to optimise Power-to-X pathways in renewable energy, but their integration for district heating sustainability assessment is still limited [4]. This highlights a significant research gap in developing and evaluating DH systems that are greener and more reliant on renewable energy sources, in contrast to traditional fossil fuel-based systems that continue to dominate many existing networks.

A review of the literature shows that recent advances have improved the performance of CHP plants, which generate both electricity and heat and significantly enhance the overall efficiency of DH networks. These systems often use natural gas, biomass, or waste fuels. The Copenhill Waste to Energy plant in Copenhagen is an example of an efficient CHP DH system, achieving thermal efficiencies of 107 % and reducing its carbon footprint [16]. In the UK, companies like Edina Group and projects like the Wyndford Scheme in Glasgow demonstrate the potential of CHP systems to reduce fuel costs and CO_2 emissions [17,18].

Recent studies also highlight innovative advancements in this area. A study by [19] investigates the decoupling of heat and power production in CHP units using heat storage solutions, which enhances the operational flexibility and efficiency of district heating systems. Additionally, research by [20] explores various decarbonization strategies for district heating networks, emphasising the integration of renewable energy sources to significantly reduce carbon emissions. Another study by [21] assesses the economic and technical feasibility of coupling district heating systems with small modular reactors, presenting a promising solution for low-carbon heating. Furthermore, a study by [22] examines the integration of electric heat pumps with CHP plants, showing that such combinations can improve energy utilisation and reduce environmental impact.

Specifically, biomass-based DH systems, using sustainable fuels like wood chips and agricultural residues, can reduce emissions by 60–80 % compared to fossil fuels. These systems also generate electricity and heat, improving energy efficiency [4]. Biogas, produced primarily through anaerobic digestion, is increasingly used for CHP applications in Ireland, with plants generating 580 GWh for heat and power [23]. Despite their higher initial costs, biomass and biogas CHP systems offer substantial emissions reductions and energy savings, although challenges such as fuel handling and storage remain [11,24–26].

Another technological advancement contributing to the efficiency and decarbonisation of DH systems is the growing adoption of heat pump-based solutions, which can harness ambient, geothermal, or waste heat sources with high efficiency [27]. A notable example is the Wien Energie heat pump plant in Vienna, which extracts wastewater heat and upgrades it using renewable electricity, reducing CO_2 emissions significantly (Perišić, 2023; Codema, 2024).

And finally, waste heat from industrial processes, data centres, and power generation can be captured and used for DH, providing an environmentally friendly and cost-effective heat source. For instance, Dublin's waste heat could potentially heat over one million homes [28]. Cities like Berlin and Mannheim also utilise waste heat through heat pumps, reducing emissions by replacing fossil fuels [29]. An example of this technology is Ireland's first large-scale DH network, TDHS, which uses waste heat from Amazon's Tallaght data centre to provide heat to public buildings and the TU Dublin campus. The system plans to expand to residential and commercial buildings, reducing carbon emissions by 1500 tons annually [30–32]. The system faces challenges due to the lack of DH-specific policies in Ireland but has overcome these through EU funding and stakeholder engagement (TD, 2023).

Recent studies emphasise the potential of waste heat recovery from DCs to enhance energy efficiency and reduce environmental impacts. A study by Yuan et al. reviews various heat recovery methods in DCs, highlighting their role in district heating and other applications [33]. A novel method was suggested by Steinegger for designing supra-regional district heating networks that integrate renewable and industrial waste heat, reducing CO2 emissions and energy demand [34]. Also, another study showed that integrating waste heat from a 21 MW DC in Finland can lower CO2 emissions and costs by replacing high-emission peat [35]. These studies collectively showcase the promising role of DC waste heat in improving the sustainability of district heating systems.

DH is a relatively new technology in Ireland, currently representing <1 % of the heat market. The Irish District Energy Association (IrDEA) suggests it has the potential to become the most economically viable low-carbon heating solution for 64 % of the Irish population [36]. Heat Roadmap Europe also found that 57 % of Ireland's heat demand could be met by DH [37], along with Ireland's National Heat Study in 2022, which found 54 % of the demand could be met with DH [38]. Ireland's Project Ireland 2040 and the Climate Action Plan 2024 set ambitious DH targets, aiming for 2.7 TWh of heat supplied by DH by 2030 (TD, 2023). The DECC Climate Action Fund has allocated €24.5 million to accelerate DH infrastructure development. These targets and investments highlight the urgent need for robust, evidence-based studies to evaluate the technical, economic, and environmental feasibility of DH, ensuring it can play a central role in meeting Ireland's heating demand and decarbonisation goals.

To effectively design and assess low-carbon heating networks, advanced modelling and optimisation tools are increasingly employed to capture the complexity of energy flows and system integration. Optimisation tools like HOMER Pro have been widely used for modelling and optimising DH systems. For instance, Terkes et al. demonstrated the use of HOMER Pro for optimising the integration of renewable energy sources in district heating networks, highlighting its effectiveness in reducing operational costs and CO_2 emissions [39]. Similarly, Najeeb et al., applied HOMER Pro to model biogas-based CHP systems and reported significant improvements in energy efficiency and CO_2 emissions reductions through the optimisation of fuel usage and system configuration [40]. Vendoti et al. used HOMER Pro for a similar study of biomass and biogas CHP systems, confirming the tool's reliability for simulating operational behaviour and predicting environmental outcomes [41]. These studies underline the utility of HOMER Pro as an essential tool for evaluating and optimising low-carbon district heating solutions, with proven success in real-world applications.

1.1. Research contribution

While LCA of DH systems has gained traction in recent years, most studies focus on conventional or single-technology systems, such as fossil-based or biomass-only networks. Research on integrated renewable DH systems, those that combine multiple supply options such as waste heat recovery, renewable-based CHP, and large-scale heat pumps, remains limited, particularly from a full cradle-to-grave environmental perspective. Also, reviewing the existing research shows that the technical and economic aspects of networks and demand modelling are already well documented, while the LCA of different integrated supply options specific to DH systems is less explored. Existing studies often rarely assess the synergies and trade-offs between combined supply technologies. This leaves a significant gap in understanding the holistic environmental performance of next-generation renewable DH systems, which are increasingly central to Europe's decarbonisation strategies.

Also, existing LCAs are typically conducted in mature DH markets, which limits their relevance to the Irish context, where DH currently accounts for <1 % of total heat demand. National and EU-level studies by IrDEA, SEAI, and Codema highlight the considerable untapped potential for DH in Ireland, but a comparative, location-specific LCA that accounts for both embodied and operational emissions is still lacking. Addressing this gap is essential for informing sustainable planning, investment, and policy development tailored to Ireland's unique infrastructure and decarbonisation challenges.

The objective of this study is to address the identified gaps by developing a comprehensive Environmental LCA (E-LCA) framework for integrated DH supply solutions. The research will conduct a full E-LCA of selected pathways, including waste-heat-fed, natural gas CHP, and biogas CHP systems, capturing both embodied and operational emissions. By combining operational optimisation modelling in HOMER Pro with life cycle inventories in SimaPro (Ecoinvent database), this dual-modelling strategy provides a systems-level assessment that simultaneously evaluates operational and embodied impacts, an approach rarely applied in the existing literature. In doing so, the study will generate new insights into the synergies and trade-offs between conventional and renewable supply technologies, identify the main drivers of global warming potential, such as fuel selection, resource availability, and system efficiency, and highlight the potential of biogas as a viable low-carbon alternative. The findings will underpin evidence-based policy and design recommendations to guide the sustainable development of DH infrastructure and support Ireland's transition to low-carbon heating by 2030.

2. Methodology

This study uses an integrated approach to evaluate the environmental performance of three DH supply options: waste heat-fed, natural gas CHP, and biogas CHP, based on the current thermal demand of the TDHS. The methodology includes: (1) a LCA following ISO 14,040/14,044 standards using SimaPro and the Environmental Footprint 3.1 [42] method to capture embodied emissions from raw material extraction to system disposal; (2) detailed life cycle inventory (LCI) development using manufacturer datasheets, stakeholder inputs, and literature; (3) operational performance and emissions modelling in HOMER Pro over a 20-year project lifetime; (4) optimisation of CHP system configurations to identify the most carbon-efficient designs; and (5) two-dimensional sensitivity analysis to assess the effects of boiler efficiency and biomass availability. This combined framework provides a robust, location-specific comparison of DH supply solutions to inform low-carbon heating strategies in Ireland (Fig. 2).

The objective function was defined as the minimisation of CO_2 emissions. Model constraints ensured thermal demand satisfaction, adherence to component efficiency thresholds, and compliance with operational limits. The optimisation tool used in this work (HOMER Pro) employs an enumerative search algorithm, which systematically generates and simulates all feasible configurations within the defined design space. Each configuration is evaluated against the objective function, while infeasible solutions violating the constraints are eliminated. The feasible solutions are then ranked by performance, ensuring the identified optimal design corresponds to the global optimum within the specified parameter ranges. This process provides a robust basis for evaluating the environmental performance of the DH pathways. HOMER Pro inherently reconciles mass and energy balances by linking fuel lower heating values with electrical/thermal outputs and efficiency constraints, ensuring internal consistency across all simulated scenarios.

This research focuses on the environmental impact of various supply scenarios for a more sustainable and greener DH system. The supply solution determines the environmental performance of DH systems as the choice of energy source, biomass or fossil fuel, directly impacts GHG emissions, resource use and overall sustainability. By concentrating on supply, the analysis delivers actionable insights into the most sustainable and feasible energy sources for Tallaght's heat demand. Additionally, this focus aligns with Ireland's CAP to implement 2.5 TWh of DH as

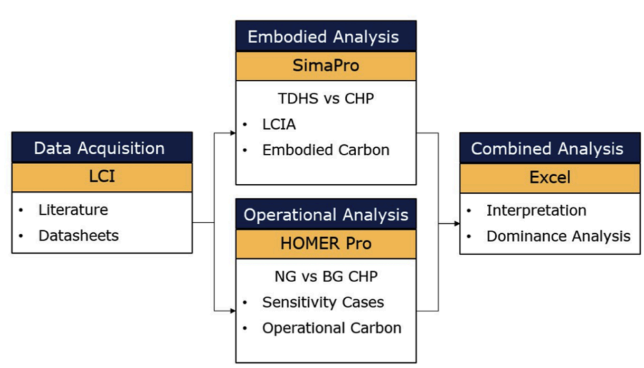

Fig. 2. Methodological framework of the study, outlining data acquisition, embodied carbon analysis using SimaPro, operational carbon modelling using HOMER Pro, and integrated interpretation via Excel-based dominance analysis.

part of decarbonisation efforts in heating [8].

2.1. Life cycle assessment

This study employs a standardised E-LCA methodology, in line with ISO 14,040 and 14,044, to evaluate the environmental impacts of DH supply systems from cradle to grave. The LCA process is structured around four key stages: (i) Goal and Scope Definition, (ii) Life Cycle Inventory (LCI), (iii) Life Cycle Impact Assessment (LCIA), and (iv) Interpretation (Fig. 3). The goal and scope phase defines the study's purpose, functional unit, and system boundaries; technical, geographical, and temporal to ensure comparability across scenarios. The LCI phase involves collecting detailed data on material, energy, emissions, and waste flows, with two recognised approaches: Economic Input-Output (top-down) and Process-Based (bottom-up). This study adopts the process-based approach for higher resolution and specificity.

The LCIA phase translates inventory data into environmental impact categories such as global warming potential, acidification, eutrophication, and toxicity. It involves classification, characterisation (e.g., using IPCC Global Warming Potential (GWP) factors), normalisation, and weighting to prioritise impacts. Due to the subjectivity in selecting and weighting categories, alignment with the study objectives is critical. For this project, LCI data were supplemented by technical datasheets from manufacturers and data from local stakeholders such as Codema and South Dublin County Council. Assumptions were made where data were not publicly available, and transport modelling was based on standard European logistics routes via ferry and road. This comprehensive and location-specific LCA framework provides a robust foundation for evaluating the embodied environmental impacts of alternative DH supply solutions in Ireland. SimaPro is widely used for LCA, integrating databases of Ecoinvent to assess environmental impacts. It is valuable for sustainable design and policy development, particularly in energy and infrastructure projects like DH [44].

The Technosphere diagram in Fig. 4 shows the technical scope of this study. The system boundary of this study includes raw material extraction to energy production in use, and disposal. In the embodied stages of it accounts for raw material extraction, component manufacturing, material and component transport and the construction of the energy infrastructure and the disposal of the infrastructure after its lifetime. Within the use stages, it includes the CHP plant or waste heat-fed energy centre, boilers and their associated electricity and fuel consumption, which lead to heat and electricity production. However, processes outside the scope of this study include upstream electricity generation, fuel extraction and the downstream energy distribution across the DH network or electrical grid. In line with standard LCA practice, the waste heat from the data centre is treated as a burden-free input, as it represents an unavoidable by-product that would otherwise be dissipated.

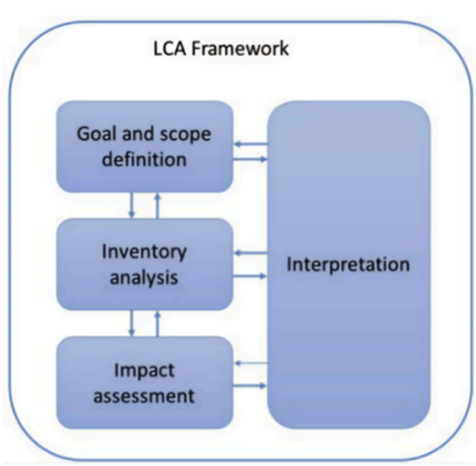

Fig. 3. Framework used in this study, illustrating its iterative nature across goal and scope definition, inventory analysis, impact assessment, and interpretation [43].

2.2. Embodied carbon analysis

The SimaPro model was selected as the primary tool for conducting the Embodied Carbon Analysis of the DH systems. SimaPro is a widely used software tool for LCA, offering a robust platform for analysing the environmental impacts of products and systems from cradle to grave. The first stage in setting up the SimaPro model involved selecting the appropriate libraries for the analysis. For this study, the Ecoinvent 3.8 system and unit libraries were selected, as well as the Methods library, which provides a variety of impact assessment methods [45]. The Ecoinvent v3.8 database is particularly valuable for this study as it contains LCI data from multiple sectors, including energy production, transportation, building materials, chemicals production, and agriculture. The dataset includes over 20,000 interlinked datasets, each representing an individual process, which enables a detailed and comprehensive LCA of various supply systems. The life cycle impact assessment for global warming potential was conducted using the IPCC 2021 (AR6) methodology, with the Ecoinvent 3.8 database providing the emission factors for all background processes. The composition of this modelled electricity mix was as follows: natural gas (53.2 %), wind (22.0 %), other renewables and wastes (7.9 %), coal (6.9 %), hydro (1.8 %), oil (1.2 %), and peat (0.8 %) [46].

Once the libraries were selected, the next step was the construction of the necessary assemblies and subassemblies in the SimaPro inventory section. Assemblies represent larger product components consisting of several subassemblies that together form the entire system. The use of assemblies and subassemblies helps modularize the modelling process, ensuring that each component's environmental impact is tracked separately before integrating them into the final product system. This approach aligns with the EN 15,804 product stage framework, which focuses on A1 (raw material supply), A2 (transportation), and A3 (manufacturing) stages.

The two assemblies compared in the study were the current TDHS plant and the proposed CHP system plant. Data for the materials and weights of the components of each assembly were sourced from previous LCA studies, including a comparison of the TDHS and a biomass-based CHP system [18], and the MWM datasheets for the gas engine [47]. Since both the natural gas and biogas CHP plants would use the same components (including the same gas engine), it was deemed sufficient to build one CHP plant for comparison in the SimaPro mode (Figs 5& 6).

The Environmental Footprint 3.1 Method was chosen for the impact assessment, along with normalisation and weighting techniques. This method is part of the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) framework developed by the European Commission, ensuring that the study aligns with EU sustainability goals. The EF 3.1 method offers consistency and comparability across multiple impact categories, and it enhances decision-making by prioritising environmental impacts based on their significance. Normalisation scales the results relative to a European reference system, making it easier to interpret the relative environmental burdens across systems. Weighting further refines this analysis by assigning values to each impact category, helping to prioritise actions based on their environmental significance. This approach ensures that the environmental impact of different DH supply options is assessed comprehensively and aligned with EU sustainability standards. The impact categories assessed using the Environmental Footprint Method are represented in Table 1.

2.3. Optimisation of operational carbon

The optimisation of the DH supply systems was carried out using a

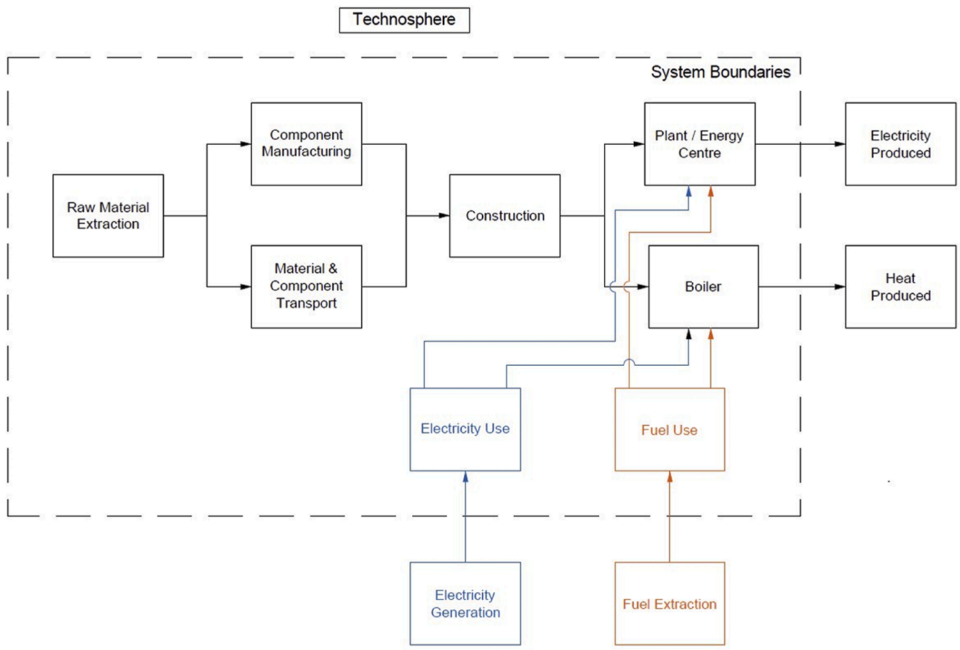

Fig. 4. Technosphere of the study, illustrating the system boundaries, material and energy flows, and main processes considered, from raw material extraction through to energy conversion and final outputs (electricity and heat).

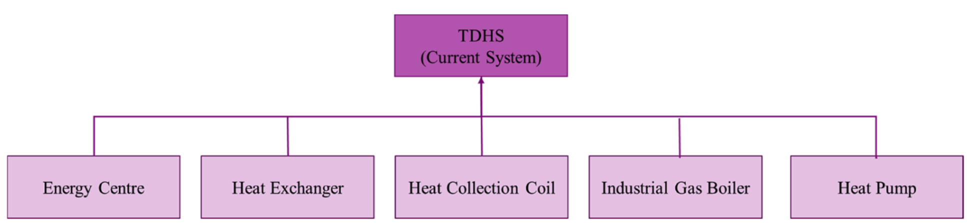

Fig. 5. TDHS current system assembly in SimaPro.

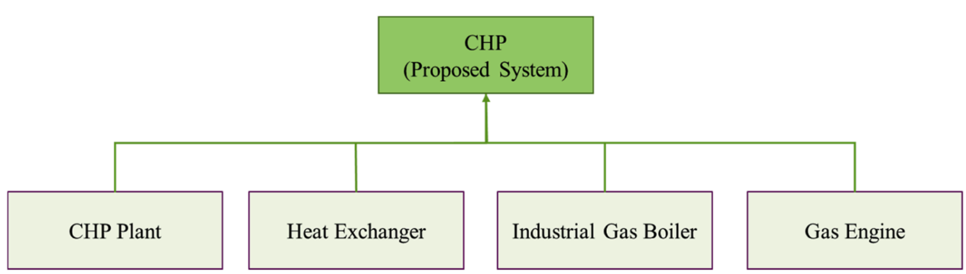

Fig. 6. CHP (proposed system) assembly in SimaPro.

simulation optimisation approach implemented in HOMER Pro. The system model comprised three main components: a biogas-based CHP unit modelled on the MWM TCG 2020 V16 gas engine, a natural gas boiler for supplementary heat, and a thermal load controller. The optimisation was designed to identify configurations that minimise total annual CO_2 emissions while consistently meeting the thermal demand. Key input parameters included fuel type (natural gas and biogas), candidate CHP capacities (800 kW, 1000 kW and 1380 kW), annual operating hours (8760), and system efficiencies (e.g., 95 % for the boiler). The primary decision variables were the generator capacity, annual fuel consumption, and resulting CO_2 emissions.

The HOMER Pro model was configured to simulate and optimise DH supply scenarios based on the current TDHS site in Dublin. Also, HOMER Pro modelling ensures internal consistency of fuel Lower Heating Value (LHV) electrical/thermal outputs, and efficiencies. Location-specific weather and economic parameters were defined to ensure accurate modelling of thermal and electrical demand profiles. The model included a baseline scenario with a natural gas boiler representing conventional heating systems, as well as two CHP plant configurations: one fuelled by natural gas and the other by biogas. Technical specifications for these systems, including generator load limits, heat recovery ratios, and component lifespans, were based on manufacturer datasheets and relevant literature.

The GHG accounting approach in this study follows IPCC and EF 3.1 conventions. Fossil CO_2 emissions from natural gas combustion were fully accounted for, while biogenic CO_2 from biogas was treated as climate-neutral. CH_4 slip and N_2O emissions were included via HOMER Pro emission factors, whereas upstream methane leakage and digestate

Table 1
Environmental Footprint (EF) 3.1 impact categories applied in this study, as implemented in the SimaPro 9.5 software using the Ecoinvent 3.8 database.

Impact Category	Unit	Description
Climate Change	kg CO2-eq	Measures the global warming potential due to greenhouse gas emissions.
Ozone Depletion	kg CFC-11-eq	Assesses the potential impact on the stratospheric ozone layer.
Ionizing Radiation	kBq U-235-eq	Evaluates the impact of radioactive emissions on human health.
Photochemical Ozone Formation	kg NMVOC-eq	Measures the contribution to ground-level ozone formation, affecting air quality.
Acidification	mol H^+-eq	Assesses the potential for emissions to cause acid rain, affecting soil and water.
Eutrophication - Terrestrial	mol N-eq	Evaluates nutrient enrichment leading to excessive plant growth on land.
Eutrophication - Freshwater	kg P-eq	Assesses nutrient pollution leading to algal blooms in freshwater ecosystems.
Eutrophication - Marine	kg N-eq	Evaluates nutrient loading in marine environments affecting biodiversity.
Particulate Matter Formation	disease incidence	Measures the impact of fine particles on human respiratory health.
Resource Use - Fossils	MJ	Assesses the depletion of fossil fuel resources.
Resource Use - Minerals & Metals	kg Sb-eq	Assesses the depletion of mineral and metal resources.
Water Use	mÂ^3 water consumed	Evaluates the consumption of water resources and potential scarcity impacts.
Land Use	Dimensionless Pt	Assesses the impact of land occupation and transformation on biodiversity.

handling impacts/credits were not modelled due to the lack of reliable local data.

FU is defined as the annual production of 1000 kWh of heat, which is heat generated at the plant's output boundary, representing total heat demand supplied by the TDHS, and is used to normalise comparisons between TDHS and CHP systems (biogas and natural gas) based on embodied carbon emissions and operational performance, ensuring consistency across scenarios.

The natural gas and biogas CHP systems were both modelled using MWM TCG gas engine specifications, with operational characteristics adjusted for each fuel type. Biomass feedstock properties and costs were incorporated into the biogas scenario based on data from local anaerobic digestion plants. Anaerobic digestion was selected over thermal gasification due to its higher technology readiness level for biogas production in Ireland and better alignment with the available regional feedstock of agricultural waste. A Thermal Load Controller (TLC) was included to prioritise heat demand and avoid excess electricity generation, in line with the study's focus on DH rather than power production.

To evaluate the influence of key variables on system performance, a two-dimensional sensitivity analysis was conducted. This tested the impact of varying boiler efficiencies and biomass availability levels on system feasibility and emissions. The model was used to simulate a wide range of system configurations, enabling the identification of optimal solutions with the lowest carbon emissions while meeting the annual heat demand profile of the TDHS.

2.4. Case study

The TDHS is Ireland's first large-scale DH network, serving as a significant milestone in the country's transition toward low-carbon heating solutions (Fig. 7). TDHS was initiated to use the excess heat from Amazon's Tallaght data centre, addressing the high energy demand in the area while reducing reliance on fossil fuels. The project was supported by the EU's HeatNet NWE project, the Climate Action Fund, and local government investments.

The heating system captures waste heat from Amazon's data centre and distributes it through an efficiently insulated pipe network to connected buildings. The initial phase of the network supplies heat to 32,800m^2 of public buildings and the TU Dublin Tallaght campus. The system is designed for further expansion, allowing additional buildings to be integrated over time. Phase two will include Tallaght County Hall and Library, the SDCC Innovation Centre and 438 apartments as part of the Belgard Gardens complex, which will house up to 3000 residents, connecting in early 2025. This accounts for a demand of 3770,000 kWh of heat distributed per year [8].

The primary energy source is low-temperature waste heat from the data centre, supported by backup heat pumps to ensure reliability. The network is expected to deliver an initial 3 GWh of thermal energy per year. Additionally, the system includes a 3 MW electric boiler to ensure heat supply reliability.

3. Results & discussions

3.1. Embodied carbon results

The embodied carbon results from SimaPro for the current TDHS and the proposed CHP systems are analysed (Fig. 8). The analysis includes the CO_2 emissions from different components of the systems, focusing on the environmental impact of the construction stages. It is important to note that this analysis pertains only to the plants generating heat for the DH networks, excluding the pipework and distribution systems.

The two network diagrams illustrate the distribution of CO_2eq.

Fig. 7. Geographical boundary map of TDHS as a case study.

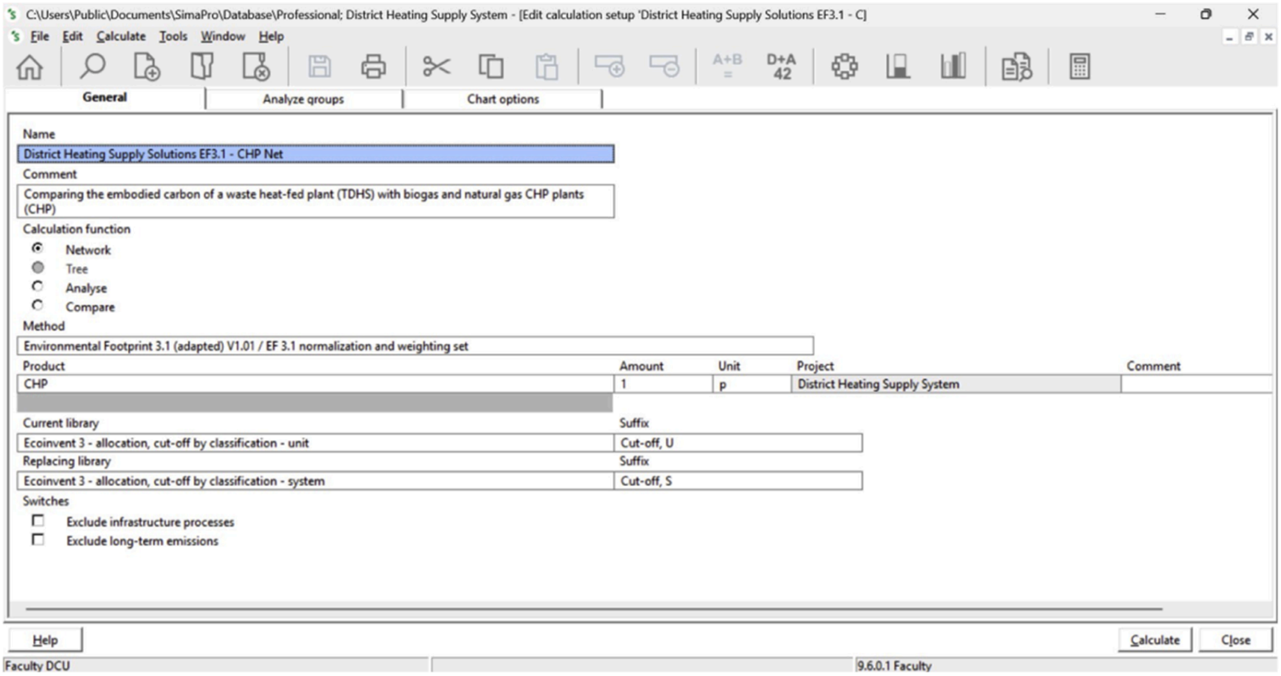

Fig. 8. LCA analysis for the CHP system, generated in SimaPro.

emissions across the various components that make up each system (Figs. 9& 10). Fig. 9 shows that the total embodied carbon of the current TDHS is 402,000 kg CO_2eq. The TDHS network diagram shows that the largest contributor to this is the construction of the Energy Centre at 199,000 kg CO_2eq. This is the building that houses most of the components for heat generation, such as the heat pump and backup boiler. Some of the main contributing factors to this include raw materials such as the foam insulation slabs and the 70m^2 concrete foundation, and processes such as the transport via road of the raw materials to the site.

Fig. 10 shows the total embodied carbon of the proposed CHP systems, which would be 256,000 kg CO_2eq. Its highest contributor is the 5 MW industrial backup boiler which is in both the TDHS and the CHP system at 83,400 kg CO_2eq. The TDHS's other components closely follow the boiler, all being between 50,300 and 67,900 kg CO_2eq.

The key distinction between the two systems lies in the substantially higher embodied carbon of the TDHS, which is 57 % greater than that of the CHP system. This difference is primarily attributed to the extensive use of insulation materials and structural steel in the TDHS network. The Energy Centre alone accounts for 199,000 kg CO_2eq—almost three times the 67,900 kg CO_2eq associated with the CHP plant—highlighting the greater carbon intensity of the TDHS infrastructure. This is likely driven by its larger material requirements and construction complexity. To mitigate this embodied carbon gap, the adoption of sustainable materials, such as recycled steel or low-carbon concrete, could substantially improve the environmental performance of the TDHS. Furthermore, optimising the distribution network design to minimise material demand offers an additional pathway to reducing embodied emissions.

A closer look at material contributions further explains this difference. The TDHS system requires 133,000 kg CO_2eq. worth of steel production, compared to 82,200 kg CO_2eq. for the CHP system,

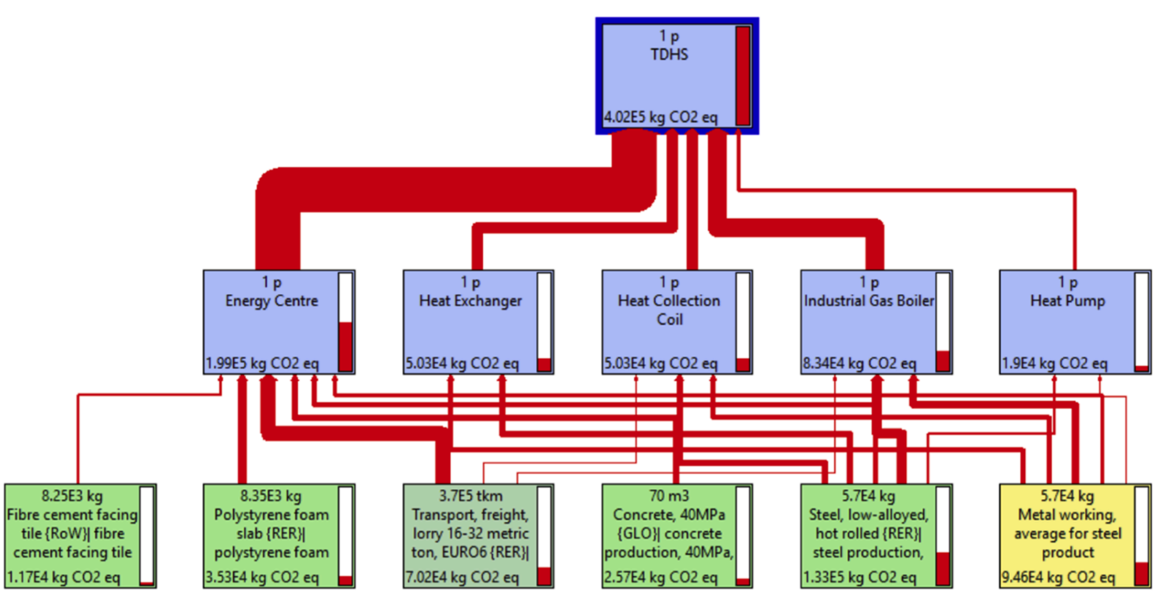

Fig. 9. SimaPro network diagram of the current TDHS, showing component-level embodied carbon (kg CO_2eq).

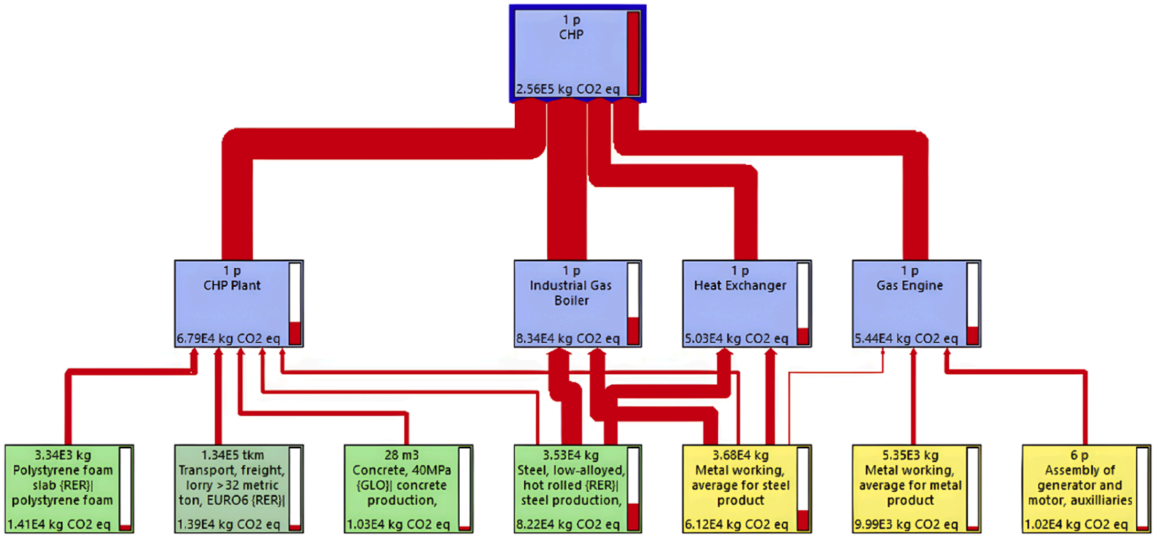

Fig. 10. SimaPro network diagram of the CHP, showing component-level embodied carbon (kg CO_2eq).

suggesting a higher reliance on steel-based infrastructure. Similarly, TDHS requires 70m^3 of concrete, emitting 25,700 kg CO_2eq., whereas the CHP plants' construction only requires 28m^3, leading to 10,300 kg CO_2eq. Additionally, metalworking processes for TDHS generate 94,600 kg CO_2eq., compared to 61,200 kg CO_2eq. for the CHP system, which supports the argument that TDHS has more resource-intensive construction.

The TDHS system exhibits higher emissions from insulation materials, contributing 35,300 kg CO_2eq., while the CHP system requires less than half of this amount at 14,100 kg CO_2eq. This difference results from the more material-intensive infrastructure of the TDHS Energy Centre. By contrast, the CHP system incurs higher transport-related emissions—13,900 kg CO_2eq. compared to 7020 kg CO_2eq. for the TDHS. This discrepancy is due to the additional logistics involved in delivering the CHP plant components, particularly the MWM gas engine, which is transported over 1418 km from its manufacturing facility in Mannheim, Germany, to the Tallaght District Heating Scheme site. The extended transport distance, involving a combination of road, rail, and sea, contributes significantly to the higher emissions associated with the CHP system.

Overall, the CHP system presents a more carbon-efficient option with a lower overall footprint despite including a gas engine and additional transport emissions. In contrast, the TDHS system relies more on material-intensive construction, particularly steel, concrete and insulation, leading to its higher embodied carbon. If the TDHS system is pursued again in the future design optimisations should be considered, such as material efficiency, alternative insulation choices and modular construction techniques to reduce its embodied carbon impact. This analysis highlights the potential benefits of opting for CHP as a more sustainable alternative in the long term.

3.1.1. Life cycle impact assessment

As discussed, the LCIA of the TDHS and CHP systems was conducted in SimaPro using the Environmental Footprint 3.1 methodology. The results are presented across four categories: normalisation, weighting, characterisation and damage assessment. The graphs of these highlight the comparative environmental burdens of each system across multiple impact categories (Figs 11–14). Across all four assessment categories, TDHS consistently demonstrates higher environmental impacts compared to the CHP system. The most critical areas of concern include climate change, human toxicity, particulate matter, resource depletion and ecotoxicity. These findings indicate that the CHP system is the more environmentally sustainable option, producing lower GHG emissions, lower toxicity-related impacts and reduced resource consumption. If the TDHS waste heat-fed system is to be pursued again, potential mitigation measures could include the selection of lower impact materials,

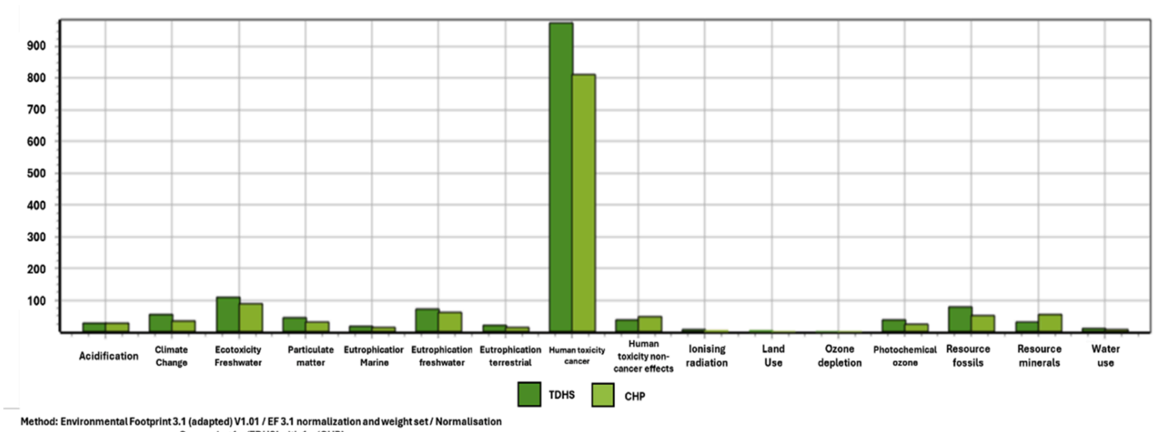

Fig. 11. *LCIA normalisation results (SimaPro):* the relative environmental impacts of the TDHS and CHP systems across multiple categories. Human toxicity (cancer effects) is the most dominant impact in both systems, with TDHS slightly higher. Other notable categories include ecotoxicity (freshwater), climate change, and resource use (fossil fuels and minerals), with TDHS consistently showing greater burdens.

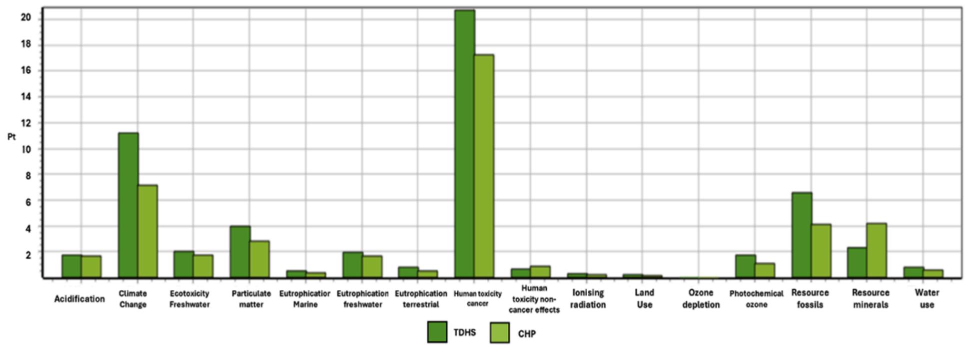

Fig. 12. *LCIA weighting results (SimaPro):* prioritise impact categories based on their significance. Climate change emerges as a key differentiator, with TDHS showing higher greenhouse gas emissions. TDHS also exhibits greater impacts in particulate matter formation and fossil resource use, indicating a heavier reliance on carbon-intensive energy and materials.

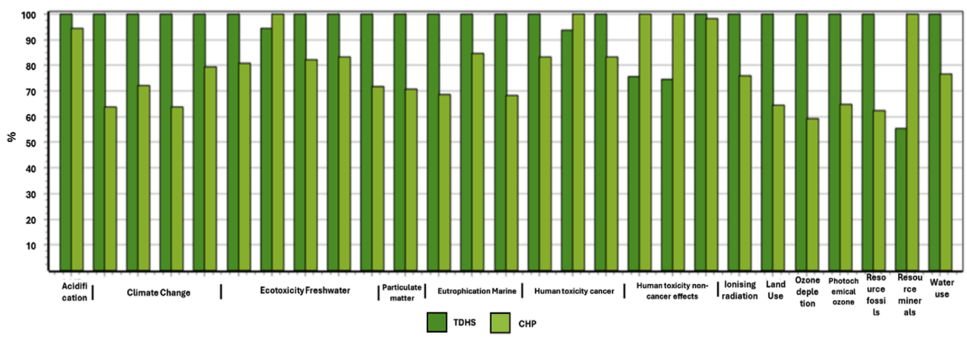

Fig. 13. LCIA characterisation results (SimaPro): the absolute magnitude of environmental impacts for both systems. TDHS consistently performs worse, particularly in acidification, eutrophication (freshwater and marine), land use, and toxicity-related categories, suggesting greater emissions of harmful compounds and more resource-intensive construction.

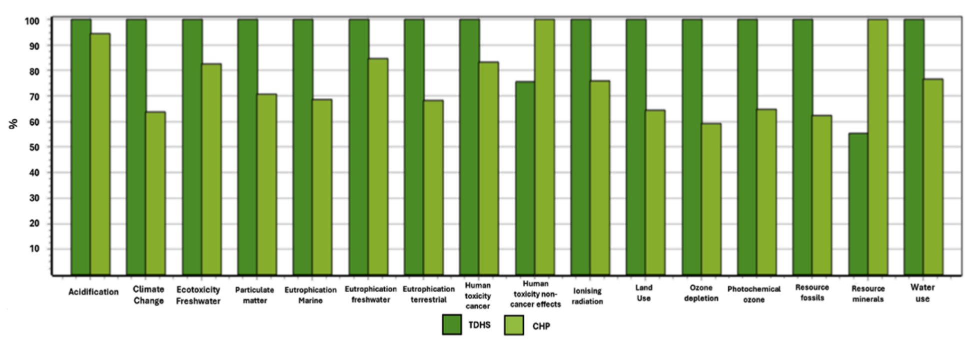

Fig. 14. *LCIA Damage Assessment Results (SimaPro):* The damage assessment evaluates overall harm to ecosystems and human health. TDHS shows higher impacts across nearly all categories, especially in climate change, ecotoxicity, resource depletion, and water use, reflecting its greater environmental burden compared to the CHP system.

improved energy efficiency and greater integration of renewable energy sources to reduce its environmental footprint. (Fig. 12, Fig. 13, Fig. 14)

There is another metric called the single score result, which provides a consolidated environmental impact comparison between the two systems. This graph aggregates various impact categories, i.e. climate change, acidification, ecotoxicity, particulate matter, and human toxicity, into a single unit for comparison (Fig. 15). It is clear that the TDHS has a significantly higher total environmental burden compared to the CHP system. The largest contributing factors in both systems appear to be climate change (green), human toxicity with cancer effects (red) and particulate matter (yellow). However, the TDHS has higher contributions across all these impact categories, supporting the trend seen in previous analyses where the TDHS consistently resulted in a greater overall environmental impact than the CHP system. The CHP system, while still contributing to environmental burdens, has a noticeably lower total score, suggesting that it is the more environmentally sustainable option. The differences in impact categories remain proportional between the two systems, meaning that the CHP system does not eliminate environmental impacts but instead reduces them across all categories.

3.2. Operational carbon results

This section presents the operational carbon emissions results comparing the natural gas CHP system and the biogas CHP system as modelled in HOMER Pro. The analysis first examines the sensitivity cases to assess the impact of boiler efficiency and biomass availability on the operational carbon emissions. This is followed by a review of the

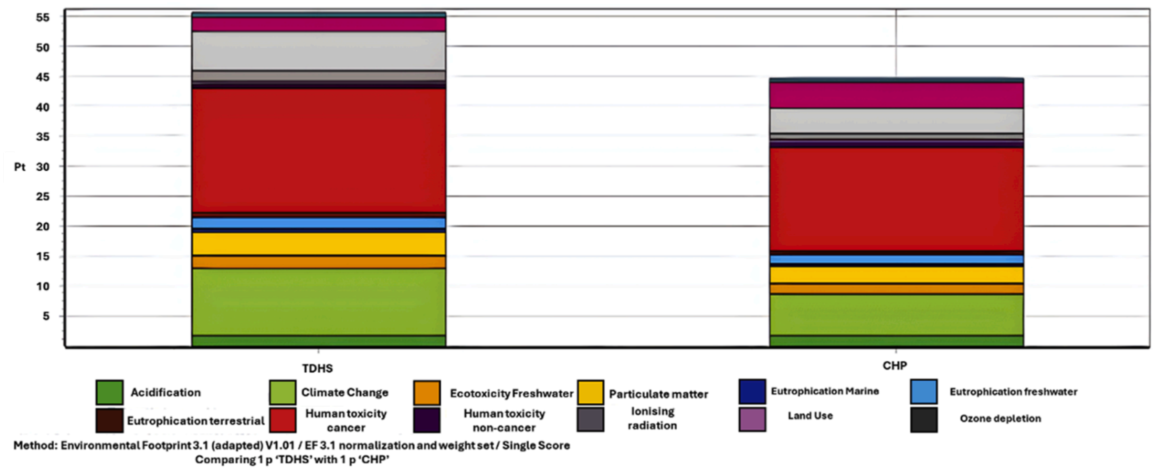

Fig. 15. LCIA SimaPro single score results for the district heating scenarios as a consolidated comparison across impact categories.

optimisation results for the lowest sensitivity cases, where the lowest operational carbon system architecture is identified and analysed in detail.

3.2.1. Model set up

The climate data was first configured using the Dublin weather data file [48]. The economic data for Ireland was inputted. Firstly, the currency was changed to the Euro €. The discount rate, the rate at which we can borrow money in %, was set as 2.90 % [49]. The inflation rate that is expected over the project life was set to 1.80 % as per the Central Bank of Ireland's projections [50]. From the literature review, it was found that the TDHS meets a thermal load of 3770,000 kWh per year, accounting for a scaled annual average of 10,328.77 kWh/day [8]. The daily load profile was set to peak in the evening, and the seasonal profile was set to peak in the colder months of November to February to match the system's real-life demand illustrated in Fig. 16 [51]. The electrical load was set to a scaled annual average of 5415.6 kWh/day. This was based on the 2023 values for average electricity consumption of an A-rated apartment per year, which is 4513 kWh/year [46].

A boiler fuelled by natural gas was added to the model. This represents the thermal demand that would have to be met by individual gas boilers in the base case of the system. It also represents the backup boiler, which will be used in cases combined with the CHP plants, for when the CHP turbine is not running. The boiler used for the E-LCA was based on the Bosch 5MW industrial boiler, which has an efficiency of 95 % [52]. Two CHP plants were added to the model. The first CHP plant added is fuelled by natural gas with a fuel price of €1.30/m3. The size in kW of the turbine was parametrically modelled to optimise which meets the demand with the lowest CO_2 emissions. Three sizes, 800 kW, 1000 kW and 1380 kW, were examined based on the MWM TCG 2020 V16 gas engine datasheet. The second CHP plant being explored in the model runs on a biogas-fuelled turbine. The bigas CHP plant is assumed to get its biogas from the Green Generation AD plant in Nurney, Co. Kildare, which has been discussed in the literature review. For this, the biomass resource was added to the HOMER model with an average price from the literature of €200/t [53]. The percentage carbon content was set to 35 % [54], gasification ratio to 0.80 kg/kg and LHV of the biogas to 24 MJ/kg [55].

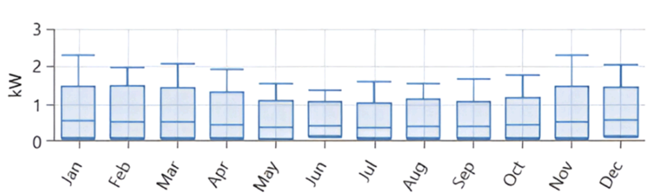

Fig. 16. Seasonal thermal load profile HOMER (scaled annual average of 10,328.77 kWh/day).

The LCA employed a conservative system boundary, focusing on combustion-phase emissions for biogas and excluding upstream processes like methane leakage or digestate credits due to data constraints. Biogenic CO_2 was treated as climate-neutral per IPCC guidelines, while fossil CO_2 was fully accounted for. An energy-based allocation method distributed environmental burdens between electricity and heat outputs, aligning with the system's primary function of heat supply.

Finally, a thermal load controller (TLC) was added to the model. Integrating a TLC into the system prioritises thermal demand, preventing excess electricity generation. Without a TLC, the model may overproduce electricity. As this study is focusing on the thermal supply to a DH network, the production of electricity alone is not necessary. Modulating CHP output ensures the system runs only when needed for heat, maximising the system's efficiency (Fig. 17).

The TLC in this model is designed to prioritise meeting the thermal demand of the district heating system while minimising excess electricity generation. The primary objective is to ensure that the thermal demand is met first, and if the thermal demand is lower than the maximum output of the CHP unit, the TLC reduces electricity generation by limiting the operation of the CHP engine to provide only the required thermal output. Once the thermal demand is met, the TLC further limits electricity generation by reducing the gas engine's electrical output,

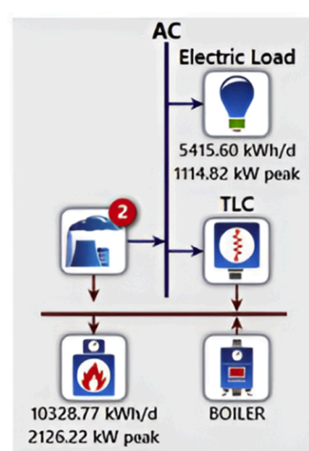

Fig. 17. System schematic generated in HOMER Pro, illustrating the configuration of the district heating scenarios. The diagram shows the generation-side components (biogas CHP, natural gas boiler, and thermal load controller) and their connections within the modelled energy system.

preventing over-generation of electricity. Additionally, in cases of excess heat generation, the TLC dynamically adjusts the operating schedule to align with heat demand fluctuations, avoiding unnecessary electricity production and ensuring efficient system operation.

3.2.2. Sensitivity cases analysis

The sensitivity analysis examined two key variables. First, natural gas boiler efficiency was tested at three levels: 75 %, 85 %, and 95 %, to assess how variations in performance affect emissions and fuel consumption. Second, biomass resource availability was evaluated across five scenarios, ranging from 1 to 5 tonnes per day, to determine the minimum supply required for the biogas-fuelled CHP system to remain feasible.

Table 2 and Fig. 18 present adapted sensitivity cases from the HOMER model, illustrating how variations in boiler efficiency and biomass availability affect the system's annual CO_2 emissions (in kg). One finding from the sensitivity cases table is that higher boiler efficiency significantly reduces CO_2 emissions. When the boiler efficiency is set at 95 % the system's CO_2 emissions remain relatively low. For example, at 95 % efficiency with a biomass supply of 3 to 5 tonnes per day, emissions remain at approximately 569,894 kg/yr. In contrast, at 75 % efficiency and still with 3 to 5 tonnes/day of biomass availability, emissions rise to 718,412 kg/yr, showing how efficiency plays an important role in minimising emissions.

Another important trend observed is that increasing biomass utilisation leads to lower CO_2 emissions for the same boiler efficiency. When boiler efficiency is 95 %, emissions for 2 tonnes/day of biomass at 702,153 kg/yr are significantly higher than for 3 to 5 tonnes/day at 569,894 kg/yr. The emissions rise even further to 1276,087 kg/yr if the biomass availability is only 1 tonne/day. A similar pattern emerges at 85 % and 75 % efficiencies, where greater biomass usage consistently results in reduced emissions. This indicates that optimising biomass supply can further enhance environmental benefits, and that the system cannot run on biogas alone if the availability of biomass is <3 tonnes/day.

The worst-case scenario in the table occurs when the boiler efficiency is lowest at 75 % and biomass availability is minimal at 1 tonne/day. This combination results in the highest CO_2 emissions at 1386,995 kg/yr, which is more than double the emissions seen in the best-case scenario of 95 % efficiency and 3 to 5 tonnes/day of biomass. This finding highlights the importance of maintaining high efficiency and adequate biomass levels to control emissions effectively.

From a sustainability perspective, both boiler efficiency improvements and increased biomass usage are essential for reducing carbon footprints. The best-case scenario in the table shows that a well-optimised system can cut emissions by over 50 % compared to an inefficient one. Therefore, energy policies and operational strategies should prioritise high-efficiency boilers and sustainable biomass availability to achieve significant environmental benefits.

Table 2
HOMER Sensitivity Cases (Boiler efficiency 75,85, 95 and biomass scaled average 3,4,5) and ranked for CO_2.

Sensitivity BOILER Efficiency (%)	Sensitivity Biomass Scaled Average (tonne/day)	System CO_2 (kg/yr)
95	3	569,894
95	4	569,894
95	5	569,894
85	3	635,416
85	4	635,416
85	5	635,416
95	2	702,153
75	3	718,412
75	4	718,412
75	5	718,412
85	2	764,297
75	2	843,104
95	1	1276,087
85	1	1325,031
75	1	1386,995

3.2.3. Optimisation results analysis

This section presents the results of the system optimisation conducted in HOMER Pro under the most favourable sensitivity conditions, aimed at identifying the DH supply configuration with the lowest operational CO_2 emissions. Fig. 19 shows the optimisation results table under the best sensitivity cases of a boiler efficiency of 95 % and 3 tonnes/day biomass availability from the HOMER model, with the system architecture being ranked based on CO_2 emissions in kg/year. The architecture icons from left to right represent the natural gas fuelled CHP, the biogas fuelled CHP, the backup boiler and the TLC. The table shows that the winning system architecture giving the lowest operational CO_2 is the 1000 kW biogas CHP, paired with the boiler and 800 kW TLC. This system produces the least operational emission at 510,894 kg/yr of CO_2. This is 72.9 % less than the natural gas CHP under the same sensitivity cases which produces 1882,292 kg/yr.

The three main components of the chosen system architecture consist of a biogas-based CHP gas engine based on the MWM TCG 2020 V16, a natural gas boiler and a thermal load controller. The gas engine produces a total of 2572,491 kWh/year with an average electrical efficiency of 51.4 %, thermal efficiency of 43.8 % under ISO 3046/1 standard and ambient conditions (25 °C, 1 bar, 30 % relative humidity) for nominal full-load consuming 938 tonnes/year of biogas. In addition to electricity, the gas engine supplies 1083,644 kWh/year of thermal energy as a byproduct to the electricity generation, supporting the overall heating demand for the DH network. The gas engine operates continuously, running 8760 h per year, which highlights its reliability and minimal startup requirements (Fig. 20).

The total feedstock consumed value of 938 tonnes/year is further broken down to an average feedstock per day consumption of 2.57 tonnes/day to run the biogas CHP system. The biogas consumption in kg per hour can be seen in Fig. 21, which also shows the highest time daily for biogas consumption being in the evening, between 18:00 and 20:00.

The 95 % efficiency boiler, which is based on the Bosch 5MW Industrial Boiler, works as a backup in the system by covering additional thermal loads. The boiler does not substitute for CHP downtime; instead, it operates in parallel whenever heat demand exceeds the CHP's thermal output. It consumes 262,786 m^3 of natural gas while generating 2465,257 kWh of thermal energy per year. The boiler's operational hours amount to 6635 h per year, with a mean thermal output of 281 kW. The system produces in total 3770,001 kWh/year, 40.5 % from the biogas CHP and 59.5 % from the boiler. This production can be seen across the year in kWh in Fig. 22.

In terms of environmental impact, the system significantly reduces CO_2 emissions compared to the natural gas-based system. The total CO_2 emissions amount to 510,894 kg/year, which is considerably lower than emissions from the less efficient system architecture configurations. Additional emissions such as carbon monoxide of 118 kg/year, unburned hydrocarbons of 53.2 kg/year and nitrogen oxides of 265 kg/year are also shown in the HOMER results Table 3.

Overall, the optimal system architecture identified by HOMER represents a well-balanced, highly efficient, and environmentally sustainable energy solution. Through the integration of a high-efficiency boiler, optimised biogas utilisation, and an effective thermal load control strategy, the system achieves substantial reductions in both fuel consumption and CO_2 emissions while ensuring reliable heat and power delivery. This configuration offers a valuable benchmark for the design and implementation of future district heating and CHP systems targeting enhanced sustainability and operational performance.

3.3. Interpretation: comparing the total carbon

The interpretation phase of the LCA aims to identify environmental hotspots, life cycle stages or components where targeted interventions

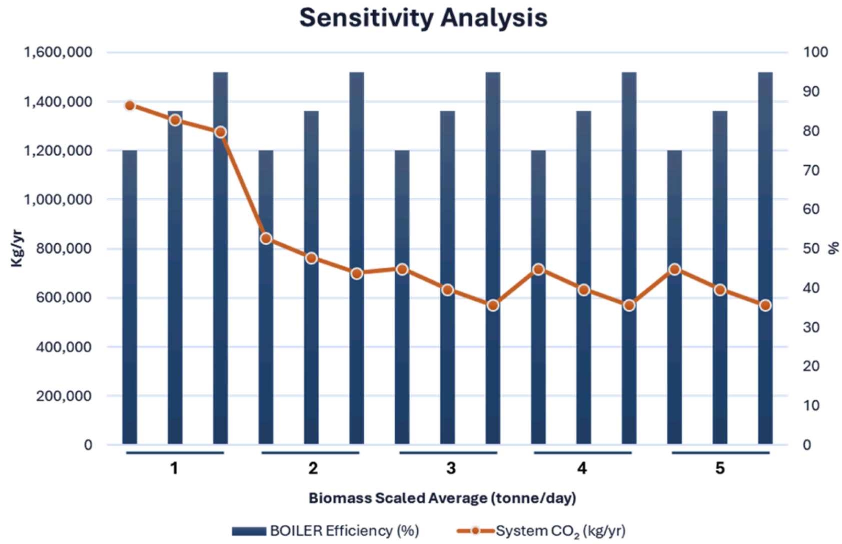

Fig. 18. HOMER sensitivity cases (Boiler efficiency and biomass scaled average) ranked for CO_2 emission.

Architecture				System		
NG CHP (kW)	BG CHP (kW)	TLC (kW)	Dispatch	Elec Prod (kWh/yr)	Therm Prod (kWh/yr)	CO_2 (kg/yr)
	1,000	800	CC	2,572,491	3,548,901	510,894
800	800	800	CC	2,332,093	3,648,834	569,894
1,000		800	CC	2,881,187	3,765,673	1,882,292

Fig. 19. HOMER Pro optimisation results ranked by annual CO_2 emissions (kg/year) under best-case sensitivity conditions.

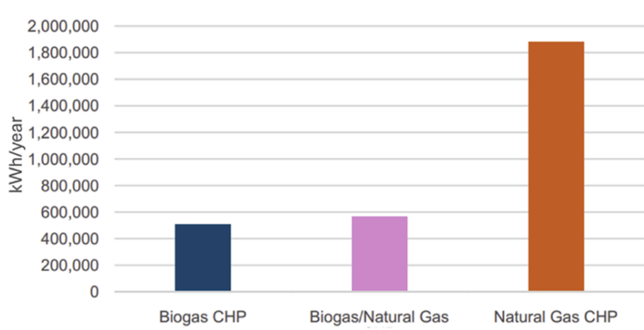

Fig. 20. Annual operational CO_2 emissions (kg/year) for three CHP system configurations: The biogas CHP system shows the lowest emissions, followed closely by the biogas/natural gas hybrid configuration. The natural gas-only CHP system has the highest CO_2 emissions, more than three times greater than the biogas CHP, highlighting the environmental advantage of renewable fuel sources.

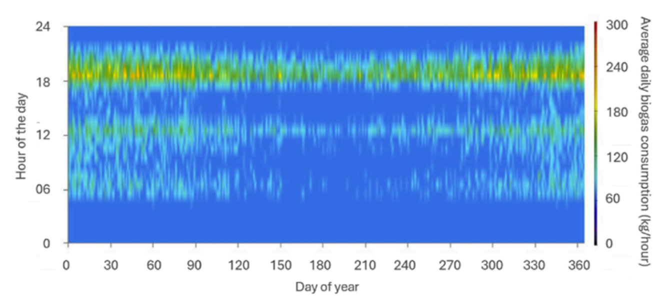

Fig. 21. Average daily biogas consumption (kg/hour).

can significantly reduce overall environmental impact. This phase also involves evaluating results, drawing informed conclusions, addressing limitations, and providing actionable recommendations. It is essential that the interpretation yields clear, decision-supportive insights, which is achieved through dominance analysis.

Dominance analysis identifies the life cycle processes with the highest environmental impact by evaluating global warming potential (GWP) across both embodied and operational phases of the proposed DH supply systems. Operational GWP emissions were obtained from the HOMER model for the CHP systems. However, due to unavailable data, the use-phase GWP of the existing TDHS could not be assessed. Emissions like CO, UHC, PM, and NO_x were excluded, as they do not contribute directly to climate change and are outside the study's scope. From the embodied carbon analysis, the SimaPro model gave kg CO_2 eq. results which directly impact climate change for the construction phase of all systems.

The analysis shows that the TDHS system has substantially higher embodied emissions than the CHP system. As outlined earlier, the main contributors to TDHS's embodied carbon are the heat collection coil, heat exchanger, and building construction. In comparison, the CHP system has a lower overall GWP, primarily from the plant and heat exchangers. This indicates that CHP systems are more environmentally efficient to construct. However, it is important to note that this comparison excludes operational emissions, which are critical for assessing long-term environmental impact (Fig. 23).

The extended dominance analysis incorporates the 20-year operational emissions of both CHP fuel variations, natural gas and biogas. Results show that the natural gas CHP system generates significantly higher GWP, with operational emissions from fuel combustion

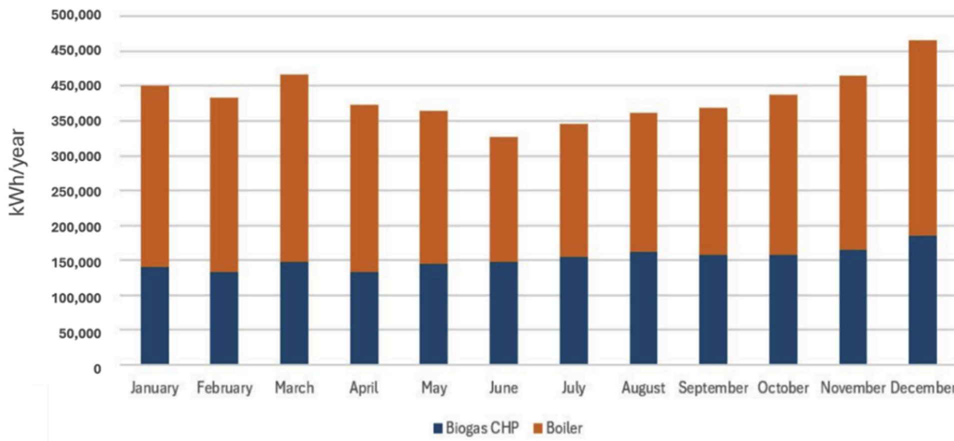

Fig. 22. Annual thermal energy production from the biogas CHP unit and the natural gas boiler (kWh/year) in the optimal district heating system configuration, as modelled in HOMER Pro.

Table 3
Comparison of Biogas CHP system emissions and Natural Gas system emissions.

Pollutant	Biogas CHP (kg/yr)	Natural Gas (kg/yr)
Carbon Dioxide	510,894	1882,293
Carbon Monoxide	118	11,262
Unburned Hydrocarbons	53.2	625
Particulate Matter	2.74	97.3
Sulfur Dioxide	0	0
Nitrogen Oxides	265	2301

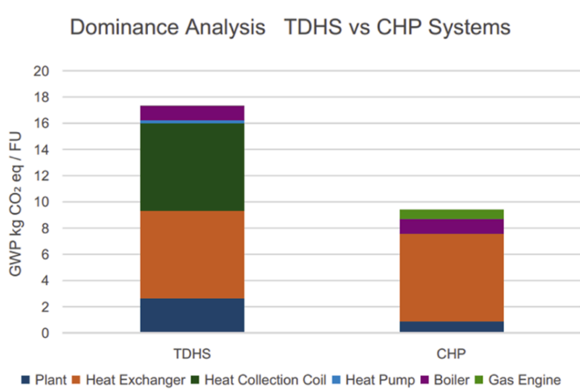

Fig. 23. Dominance analysis excluding the use phase per FU (1000 kWh of heat generated).

overwhelmingly driving its environmental impact. This underscores its limited sustainability. In contrast, the biogas CHP system exhibits a substantially lower GWP due to its renewable fuel source, making it a more climate-friendly alternative. Although both systems have embodied emissions from construction, these are minimal when compared to the dominant influence of operational emissions (Fig. 24). (Fig. 25)

Calculations to compare the total emissions of the two CHP systems FU, combining the embodied and operational emissions, gave the following results, shown in Table 4. The Natural Gas CHP system emits 502.677 kg CO_2eq. per FU, while the Biogas CHP system emits only 138.911 kg CO_2eq. per FU. This again shows the Biogas CHP system achieves approximately a 72 % reduction in CO_2 emissions per FU compared to the Natural Gas CHP system.

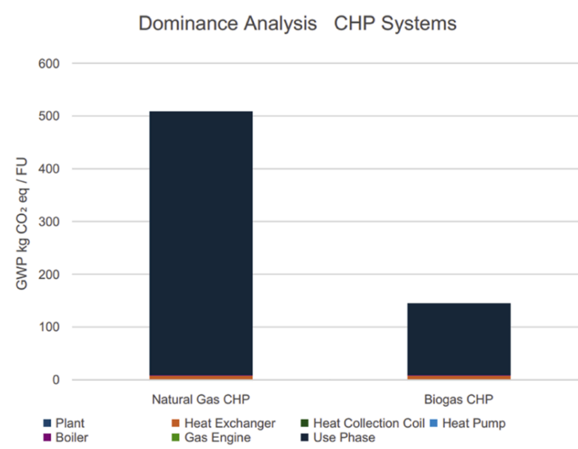

Fig. 24. Dominance analysis of the CHP systems including their use phases.

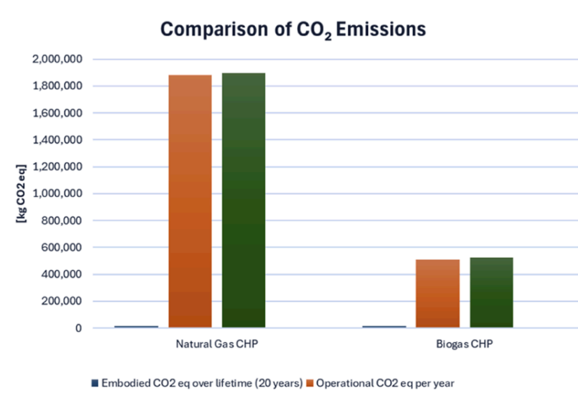

Fig. 25. Comparison of embodied, operational, and total CO_2 emissions (kg CO_2eq) for natural gas and biogas CHP systems over a 20-Year Lifetime, normalised per FU (1000 kWh of heat generated).

3.4. Discussion

The LCA results, anchored by the LCI data in Table 5, quantitatively demonstrate the environmental superiority of the optimised system, which emits 510,894 kg CO_2/year, 72.9 % reduction compared to the 1882,292 kg CO_2/year from a natural gas CHP benchmark. This significant reduction is achieved through the continuous operation (8760 h/

Table 4
Comparison of Embodied, Operational, and Total CO_2 Emissions (kg CO_2eq) for Natural Gas and Biogas CHP Systems over a 20-Year Lifetime, Normalised per FU ((1000 kWh of heat generated).

	Annualised embodied CO_2 eq per year [kg CO_2 eq]	Operational CO_2 eq per year [kg CO_2 eq]	Total Emissions per year [kg CO_2 eq]	Total Emissions per FU [kg CO_2 eq]
Natural Gas CHP	12,800	1882,292	1895,092	502.677
Biogas CHP	12,800	510,894	523,694	138.911

* **Note:** Annualised embodied CO_2 was calculated as total embodied CO_2 over 20 years (256,000 kg) divided by system lifetime (20 years).

Table 5
LCI for the optimal district heating system configuration (1000 kW biogas CHP, 5 MW natural gas boiler, TLC).

	Category	Parameter	Value	Unit
Inputs	*Resources*	Biogas Consumed	938	tonnes/ year
		Natural Gas Consumed	262,786	m^3/year
	Energy	Total Thermal Energy Produced	3770,001	kWh/ year
		Total Electrical Energy Produced	2572,491	kWh/ year
The key LCA results				
Outputs	*Emissions to Air*	Carbon Dioxide (CO_2)	510,894	kg/year
		Carbon Monoxide (CO)	118	kg/year
		Unburned Hydrocarbons	53.2	kg/year
		Nitrogen Oxides (NOx)	265	kg/year
System Performance	*Efficiencies*	CHP Electrical Efficiency	51.4	%
		Boiler Thermal Efficiency	95	%
	Operation	CHP Operational Hours	8760	hours/ year
		Boiler Operational Hours	6635	hours/ year
		Average Daily Biogas Consumption	2.57	tonnes/ day

year) of the efficient (51.4 %) biogas CHP unit, which supplies 40.5 % of the thermal demand with a very low carbon footprint, and is supplemented by a high-efficiency backup boiler, highlighting the critical role of fuel source and operational strategy in minimising the carbon footprint of district heating.

The operational carbon emissions calculated by the HOMER Pro model align closely with values reported in the literature, validating our approach. Our finding that the biogas CHP configuration emits 510,894 kg CO_2/year to deliver 3770,000 kWh of heat is consistent with the low-carbon profile of anaerobic-digestion-derived energy reported by [56], who found emission factors for biogas CHP typically range from 0.05 to 0.15 kg CO_2eq/kWh. This corresponds to 188,500–565,500 kg CO_2eq for the proposed output, within which our result falls. Conversely, the emissions from the natural gas CHP benchmark (1882,292 kg CO_2/year) correspond to an emissions factor of approximately 0.5 kg CO_2/kWh$_{th}$, which lies within the expected range of 0.4–0.6 kg CO_2/kWh for natural gas combustion reported by [57]. The 72.9 % reduction observed by switching to biogas is therefore numerically validated and reflects the significant carbon-avoidance potential of decarbonising district heat sources [58].

Broader findings are also supported by comparative studies on DH infrastructure. The observation that a transition to TDHS incurs 57 % higher embodied carbon due to extensive piping networks is a recognised trade-off. The author found that the upfront carbon cost of DH infrastructure is typically offset over time by operational savings from more efficient, centralised generation precisely the scenario our operational results demonstrate [59]. The electrical efficiency of the proposed MWM TCG 2020 V16 engine (51.4 %) is also technologically credible and matches the high-performance end of reported values for similar industrial-scale gas engines [60]. Taken together, this multi-faceted validation against published data on emissions factors, efficiency, and system trade-offs strengthens the credibility of the proposed model and the robustness of our conclusions regarding the environmental viability of biogas-fed CHP for DH.

The dominance analysis reinforces a core LCA principle: in energy conversion systems, the use phase almost invariably outweighs the embodied carbon of infrastructure which is aligned with the results of this research [61]. Although the embodied emissions of both CHP systems are similar (12,800 kg CO_2eq), their operational emissions diverge sharply, with 502.68 kg CO_2eq/FU for the natural gas system versus 138.91 kg CO_2eq/FU for the biogas system a 72.4 % reduction. This supports the established consensus that the carbon intensity of the fuel source is the primary driver of climate impacts in thermal energy systems [62]. The scale of operational emissions from natural gas combustion (1882,292 kg CO_2eq/year) highlights its GWP impact, offsetting any advantage from its marginally lower embodied carbon compared with the TDHS. By contrast, the biogas system's substantially lower operational footprint, attributable to biogenic carbon, underscores its role as a critical decarbonisation pathway. These findings emphasise that strategic interventions targeting fuel substitution deliver far greater reductions in overall carbon footprint than measures focused solely on improving material efficiency in construction.

In summary, while embodied emissions are non-negligible, they are far outweighed by operational emissions over a system's lifetime. Fuel source selection therefore emerges as the decisive factor in determining the sustainability of DH systems. The biogas CHP system provides the most sustainable alternative, owing to its substantially lower emissions. These results confirm that the use phase is the dominant contributor to the overall environmental impact of DH systems, underscoring the importance of fuel choice in long-term sustainable decision-making. Future strategies should also explore further decarbonisation opportunities, such as integrating renewable energy sources and improving system efficiency to minimise carbon emissions.

4. Conclusions and future recommendations

This study conducted a LCA of DH systems in Ireland, with the aim of providing a transparent comparison of both embodied and operational carbon footprints across alternative supply solutions. Three scenarios were assessed: the current waste heat–fed Tallaght District Heating Scheme, a natural gas–fuelled CHP system, and a biogas–fuelled CHP system. The analysis applied an integrated framework, combining life cycle inventory and impact assessment in SimaPro with techno-economic and operational modelling in HOMER Pro. This approach enabled a detailed evaluation of how infrastructure choices, fuel type, and operational performance interact to determine the sustainability of district heating pathways in the Irish context. Key findings include:

- The embodied emissions of the TDHS were found to be 57 % higher than the CHP systems, with 402,000 kg CO_2eq. compared to 256,000 kg CO_2eq. for the CHP systems. The Energy Centre in the TDHS is the primary source of these emissions, contributing 199,000 kg CO_2eq., largely due to steel, concrete, and insulation materials used in its construction. This highlights that the TDHS system is more resource-intensive during construction.
- The LCIA revealed that the CHP systems have a lower environmental footprint across various impact categories, including climate change,

human toxicity, and particulate matter, with the TDHS exhibiting higher environmental burdens in these areas.
- The operational phase accounts for the majority of the total carbon footprint. The sensitivity analysis and optimisation in HOMER Pro identified that a biogas-fuelled CHP system significantly reduces lifetime operational emissions compared to natural gas if biomass availability exceeds 3 tonnes/day. The biogas CHP system emits 510,894 kg CO_2/yr, a 72.9 % reduction compared to the natural gas CHP system (which emits 1882,292 kg CO_2/yr).
- Over a 20-year lifespan, the biogas CHP system emits 138.911 kg CO_2eq. per FU, while the natural gas CHP emits 502.677 kg CO_2eq. per FU. This demonstrates that both fuel choice and system efficiency optimisations are crucial for improving sustainability.
- The study concludes that, in terms of embodied carbon, the biogas CHP system is a more environmentally sustainable solution for district heating in Ireland compared to the waste heat-fed TDHS, due to its significantly lower construction-related emissions. Moreover, the biogas CHP system offers substantial long-term environmental benefits due to its reduction in operational emissions while maintaining energy reliability. However, due to the lack of data on the operational emissions of the waste heat-fed TDHS, its overall sustainability relative to the biogas CHP system remains uncertain.

To enhance the sustainability of district heating in Ireland, the findings of this study point to several targeted directions. Because the results demonstrated that operational emissions overwhelmingly dominate life-cycle impacts, the choice of fuel is critical. Expanding the role of biogas, through reliable supply chains and integration of anaerobic digestion plants, could substantially reduce carbon footprints, particularly when biomass availability exceeds the identified threshold of 3 tonnes/day.

The comparison also highlighted the high operational emissions of natural gas CHP, reinforcing the need to shift away from fossil-based options. At the same time, the lack of reliable data on the use-phase profile of the waste heat–fed TDHS introduces uncertainty, suggesting that policy instruments should remain adaptive and evidence-based, evolving as more operational data and pilot studies become available. Together, these findings suggest that prioritising renewable fuels, ensuring robust supply conditions, and designing flexible policy frameworks are essential for supporting the long-term decarbonisation of district heating in Ireland.

Based on these findings, some implications for stakeholders can be cautiously drawn. Targeted support mechanisms, such as green gas certificates or feasibility grants, may be more effective in the short term than broad mandates, particularly given the early stage of DH deployment in Ireland. Policy measures should remain flexible and capable of evolving as further evidence becomes available from pilot projects and ongoing research.

Future research should build on this framework by integrating advanced sensitivity, seasonal variations and uncertainty analyses into HOMER Pro optimisation and LCA modelling, enabling a more robust evaluation of biomass availability, boiler efficiency (seasonal/part-load), and embodied versus operational carbon trade-offs in renewable energy district heating supply systems such as biogas CHP and waste heat–fed DHs.

CRediT authorship contribution statement

Sean O'Brien: Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Zain Ul Abdeen Qureshi:** Writing – review & editing, Visualization, Validation. **Reihaneh Aghamolaei:** Writing – review & editing, Supervision, Software, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Sean O'Brien reports financial support was provided by Dublin City University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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