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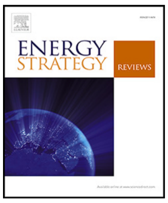

Social dimensions of energy transition: HYSTORE project stakeholder insights

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ABSTRACT

The global transition to low-carbon energy systems hinges on the adoption of technologies that are socially acceptable, technically feasible, and regionally relevant. This qualitative study, conducted within the EU-funded HYSTORE project, examines stakeholder perceptions of hybrid thermal energy storage (TES) and demand-side management (DSM) across demonstration sites in Spain, Austria, Sweden, and Ireland. Using twenty-three semi-structured interviews with policymakers, engineers, facility managers, and resident-users, the study explores economic, technical, and regulatory factors influencing adoption. The interviews followed a guide with predetermined topics, enabling structured inquiry while allowing interviewees to freely express concerns, raise new issues, and engage in meaningful dialogue. Thematic analysis reveals that around 70% of participants currently use energy storage — mainly hot-water tanks or batteries. Approximately 86% are familiar with TES, and 16 out of 23 believe TES systems are effective for improving energy management by reducing consumption and costs. Two-thirds of respondents identify photovoltaic panels as the most accessible low-carbon technology. Despite these favourable perceptions, stakeholders cite high upfront costs, limited awareness, integration complexity, and maintenance concerns as key barriers. This study provides a user-centred evidence base for the deployment of TES and DSM technologies, emphasising the need to reduce financial barriers, simplify system architectures, and enhance training and communication for installers and end-users. By grounding technical development in stakeholder experience, the research offers actionable insights for policymakers, industry practitioners, and researchers working to scale sustainable energy solutions across diverse European contexts.

1. Introduction

The HYSTORE project is a European initiative dedicated to the development and validation of advanced hybrid thermal energy storage (TES) systems. This paper is a direct outcome of HYSTORE project activities, particularly focusing on pilot audits, stakeholder roles, and use case definitions. The project integrates innovative technologies, including all-in-one phase change material (PCM) solutions, low-temperature PCM heating and cooling, PCM heating, and thermochemical material (TCM)-based heating and cooling for applications in heating, cooling, and domestic hot water configurations.

The present article analyses HYSTORE's stakeholder-interview dataset and pilot evidence to derive generalisable principles for hybrid latent/sensible TES and DSM integration. The project leverages stakeholder interviews and real-world pilot demonstrations to understand user needs and inform system design. The consortium, comprising 18 entities from eight EU countries, covers the entire TES value chain and conducts multi-site demonstrations at four pilot sites in Spain, Austria, Sweden, and Ireland, representing diverse climatic conditions from Mediterranean to subarctic climates (Köppen Geiger classification) [1].

These pilot audits are central to the HYSTORE project, facilitating real-world validation of TES technologies and enabling a comprehensive analysis of stakeholder roles and use case definitions. HYSTORE prioritises cost-effectiveness, scalability, and replicability while mapping stakeholders' beliefs and needs to develop a user evaluation model that ensures the TES systems meet diverse socio-economic and climatic demands. This study, consistent with the overarching objectives of the project, aims to develop scalable and sustainable energy solutions that are informed by stakeholder engagement and

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grounded in context-specific use case requirements. Despite substantial research in renewable energy technologies and energy efficiency measures, significant gaps persist in integrating user-centric perspectives, particularly in aligning technological advancements with diverse regional and stakeholder-specific needs. Previous studies often lack geographic diversity, context-awareness, or comprehensive stakeholder engagement. Although numerous studies have examined stakeholder engagement in energy transitions and the technical performance of TES systems, a systematic, cross-climate comparison of diverse actor perspectives remains absent. In particular, while research on battery storage adoption and demand-side management has proliferated, the integration of user feedback into the iterative design of TES has not been empirically demonstrated. Therefore, this paper investigates how policymakers, engineers, residents, and other stakeholders across four distinct European climates perceive energy storage and flexibility technologies, and how their insights can directly inform both deployment strategies and upstream TES design refinements.

1.1. The global energy transition towards sustainability and efficiency

The global energy transition is a strategic response to the interconnected challenges of climate change, energy security, and sustainable development. The "energy transition" is the societal shift from conventional energy systems to sustainable alternatives, such as renewable energy. It involves integrating innovative sustainable technologies to manage grid challenges and achieve a cleaner, more resilient energy future. It aims to reduce dependence on fossil fuels while promoting the adoption of renewable energy sources (RES), requiring systemic changes across infrastructure, economic systems, and societal behaviours. Enhancing renewable deployment and improving energy efficiency are central to lowering greenhouse gas (GHG) emissions, reducing costs, and fostering resilience in energy systems [2]. RES such as PV, wind, geothermal, and bioenergy have proven effective in reducing the carbon intensity of energy production. Declining costs of solar PV, supported by policy measures, have facilitated global uptake, including financially constrained settings such as Lebanon [3]. Moreover, geothermal energy supports low-carbon district heating, particularly in geologically favourable regions [4], while combined heat and power (CHP) systems increase efficiency by recovering waste heat [5].

Energy efficiency remains a foundational element of the transition, offering cost-effective reductions in consumption and peak demand. Measures such as DSM, advanced insulation, and high-efficiency appliances are likely to become valuable solutions across sectors. DSM programmes, in particular, help optimise energy use, reduce grid stress, and defer infrastructure investment [6]. Nonetheless, adoption is hindered by high upfront costs, limited consumer awareness, and fragmented governance. The integration of technologies such as energy-efficient HVAC systems and advanced lighting solutions required coordinated stakeholder engagement and is most effectively facilitated by targeted incentives and supportive policy frameworks [7]. TES systems are essential for increasing the flexibility of energy networks, particularly in accommodating the variability of solar and wind power. TES stores excess energy as heat or cold for later use, reducing fossil fuel reliance in heating and cooling and enhancing grid stability [8]. Technologies range from sensible heat systems using water or concrete, to more compact latent heat systems employing phase change materials. Despite their benefits, TES deployment faces obstacles such as high capital costs, complex installations, and limited user awareness, which can be mitigated through research and development investments, workforce development, and education [3].

The combined application of RES, efficiency measures, and TES has yielded tangible reductions in energy consumption, GHG emissions, and exposure to market volatility. TES in particular enables optimal RES utilisation and reduces waste and peak demand [8]. However, implementation continues to face technical, installation, and management challenges. Integrating RES with existing grid infrastructure demands advanced engineering and significant investment [9], while deployment is often constrained by labour shortages and site limitations. At the governance level, fragmented structures and the absence of standardised protocols limit scalability and project coordination [10].

Table 1
Nomenclature.

Abbreviation	Definition
CHP	Combined heat and power
DR	Demand response
GHG	Greenhouse gas
HP	Heat pump
PCM	Phase change material
PV	Photovoltaic
RES	Renewable energy sources
TES	Thermal energy storage
DSM	Demand-side management
TCM	Thermochemical material

Despite significant technological advancements, the transition towards a sustainable energy system remains impeded by challenges that extend beyond engineering and infrastructure. A main barrier is the recurrent misalignment between innovative energy technologies and the social values, expectations, and lived experiences of communities. This disconnect can delay or even derail progress. For example, although renewable energy technologies frequently garner widespread national support, local resistance to wind energy developments remains prevalent — stemming not only from concerns regarding visual impact, noise, and environmental disruption, but also from more fundamental issues related to procedural justice and the equitable distribution of benefits [11]. Similarly, the deployment of smart meters – despite their technical advantages for grid optimisation – has been hindered by public apprehensions regarding data privacy, individual autonomy, and unclear personal value [12]. Moreover, technologies such as rooftop PVs and electric vehicles, while environmentally advantageous, risk exacerbating social inequalities. For instance, affluent households are more likely to become energy 'prosumers,' whereas lower-income groups may disproportionately shoulder infrastructure costs [13]. These examples underscore the critical importance of addressing social dimensions in energy policy. Failing to do so can result in ineffective interventions, inefficient resource allocation, and a less equitable transition.

1.2. The role of user-centric approaches and stakeholder engagement in advancing energy transitions

Stakeholders – defined as individuals, groups, or organisations with a vested interest in a given project – play a central role in shaping project outcomes and long-term viability. These actors may be internal or external, ranging from employees and customers to government agencies and community members [14]. Their engagement ensures alignment with project objectives, supports resource mobilisation, mitigates risk, and enhances legitimacy. Stakeholder feedback serves as a mechanism for continuous improvement, regulatory compliance, and conflict resolution [15]. User-centric approaches are methods for developing technology that prioritises the needs and perspectives of end-users and communities. They aim to make solutions more suitable and accessible by involving users in the design and evaluation process, ensuring technology aligns with societal needs. These approaches are essential for advancing energy efficiency, sustainable energy technologies, TES, and demand response (DR) initiatives, prioritise end-user needs and behaviours to ensure solutions are technically effective, socially acceptable, and economically feasible. Stakeholder interviews with policymakers, industry experts, consumers, and technology providers uncover key barriers and practical considerations, bridging the gap between innovation potential and real-world implementation. For example, research on low-carbon energy systems has shown how user-centric methodologies can identify adoption obstacles – such as cost, regulatory complexity, and behavioural inertia – and support the design of context-sensitive interventions [16].

In the context of energy efficiency, stakeholder interviews have highlighted how high upfront costs and limited awareness deter investment in technologies such as advanced insulation, smart lighting, and optimised HVAC systems. Specifically, interviews with energy advisors in Germany revealed that targeted incentives and clear regulatory structures are essential for making efficiency measures accessible and financially attractive [17]. Engaging users directly helps ensure that implemented solutions maximise both cost savings and environmental outcomes. Stakeholder engagement is the process of systematically involving diverse groups, including policymakers, industry experts, and residents, in a project. This is done to align objectives, manage risks, gather feedback, and ensure the successful acceptance and implementation of new technologies. Sustainable technologies, including solar PV and geothermal systems, similarly benefit from stakeholder-informed approaches. In Lebanon, for instance, interviews in the solar market revealed that despite widespread support for the environmental benefits of PV systems, concerns around investment costs and regulatory barriers persist [18]. This highlights the importance of policies that both incentivise adoption and simplify system integration. Similarly, while TES technologies hold promise for enhancing long-term energy stability and efficiency, stakeholder interviews have revealed significant barriers to their adoption, including high upfront investment costs, technical complexity, and limited awareness among end users [8]. Effective communication of long-term benefits and the development of standardised assessment metrics are necessary to enhance user confidence and facilitate broader market uptake.

DR programmes also rely heavily on stakeholder engagement to identify viable pathways for implementation. Interviews with aggregators and energy providers in Germany revealed that inadequate incentives and implementation complexities in industrial contexts hinder progress. Nonetheless, stakeholder insights pointed to opportunities for aggregators to reduce entry barriers and increase programme participation through risk-mitigation tools and awareness campaigns [19]. This demonstrates the importance of participatory design in developing DR measures that align with user capabilities and system-level goals. Overall, stakeholder interviews are indispensable for revealing misalignments between actors that can obstruct energy transition initiatives. For instance, although energy efficiency is widely supported at the policy level, stakeholder interviews conducted in Germany indicate that its implementation is frequently hindered by bureaucratic inertia and fragmented or inconsistent incentive structures. Dialogue among stakeholders can help harmonise objectives, streamline procedures, and build consensus on shared priorities [17]. Through these mechanisms, stakeholder engagement fosters more coherent, inclusive, and actionable energy strategies.

1.3. Literature review

While a growing body of research has explored energy efficiency, sustainable technologies, TES, and DR, many studies lack an integrated, user-centric perspective and do not address stakeholder diversity or geographic scalability. In line with these insights, recent contributions emphasise that the success of energy transitions is strongly mediated by stakeholder dynamics, governance frameworks, and socio-political contexts – whether in wind energy projects in Mexico [20], hydrogen policy in Germany [21], mini-grid deployment in Mozambique [22], or energy harvesting in water networks [23]. For instance, Prenner et al. [24] examine second-life batteries as cost-effective energy storage solutions but highlight regulatory ambiguities and limited market acceptance as major barriers to widespread adoption. Similarly, Ragosa et al. [25] identify fragmented governance as a key constraint in promoting energy efficiency across interconnected electricity markets, while Andersson et al. [26] discuss institutional inertia and misaligned priorities that delay energy-efficient practices. These findings collectively suggest the need for harmonised policies, financial incentives, and public education to overcome systemic obstacles. Studies focused on retrofitting, such as Bergman et al. [27], point to inconsistent policies and inadequate financing as enduring barriers to residential energy upgrades in the UK. In the commercial sector, Granderson et al. [28] underscore a lack of contractor expertise and technical skills that hampers the implementation of energy-saving technologies. Although performance evaluation tools are promising, many lack field validation, reducing their practical relevance [29]. Likewise, Haghi et al. [30] provide important financial analyses of retrofit investments but do not sufficiently address scalability across different building types and operational contexts.

Research on sustainable energy technologies has advanced the understanding of innovation and governance challenges. For instance, Meirbekova et al. [31] highlight the high costs, regulatory delays, and logistical hurdles associated with geothermal development, stressing the need for region-specific policy frameworks. Cunial et al. [32] demonstrate how outdated regulations inhibit renewable innovation, particularly in solar and wind energy. Wright et al. [33] discuss the technical and governance barriers to microgrid integration, emphasising the need for adaptive approaches. Additional insights from Zohar et al. [34] and Yoo et al. [35] point to the influential role of local governance and institutional frameworks in shaping renewable energy uptake. However, these studies often neglect practical mechanisms for incorporating TES and DSM into energy systems. Moreover, the financial risks associated with scaling RES remain insufficiently addressed, with Gandhi et al. [36] calling for robust de-risking strategies to facilitate broader adoption.

TES has received increased attention for its role in stabilising energy systems and supporting renewable integration. For example, Gohari et al. [37] reveal that fragmented institutional responsibilities and regulatory gaps hinder the integration of TES into positive energy districts. Similarly, Jayaprabha et al. [8] identify high capital costs, regulatory uncertainty, and low technical awareness as major adoption barriers. Although Laubscher et al. [38] propose innovative TES business models, the lack of attention to regional and climatic variability limits their generalisability. These findings highlight the need for financial innovation, inclusive stakeholder engagement, and regulatory coherence to accelerate TES deployment. Furthermore, DSM and DR remain critical for enhancing grid flexibility but face persistent challenges. Baldwin et al. [6] raise concerns about centralised governance models and advocate for decentralised frameworks involving local actors. Stede et al. [19] emphasise the role of intermediaries in enabling industrial-scale DR but provide limited guidance for smaller-scale applications. Similarly, Sisinni et al. [39] examine DR strategies within European markets but do not offer transferable models adaptable to diverse regional or climatic contexts. Table A.1 presents a comparative overview of the selected literature reviewed in this study. It summarises key attributes of 22 studies focused on various low-carbon energy technologies, including their technological focus, addressed barriers, implementation scales, research scopes, methodological approaches, and principal findings. The table illustrates the predominance of qualitative methodologies, particularly stakeholder interviews and case studies, and highlights recurring barriers such as regulatory uncertainty, financial constraints, and coordination challenges.

1.4. Novelty and contributions

The integration of sustainable energy technologies requires comprehensive, scalable, and context-aware approaches that address critical gaps in existing research. To the best of the authors' knowledge, this study constitutes the first multi-country, stakeholder-inclusive validation of a unified TES–RES–DSM framework. Previous studies often lack generalisability, geographic diversity, or a holistic focus. For example, research on electric vehicle battery reuse [40] and local energy trading [41] has been limited in scope, often overlooking broader market applicability and the integration of technologies such as TES. Similarly, studies on renewable energy adoption in Africa [42] or cross-border collaboration within the EU [37] do not offer solutions applicable to diverse socioeconomic and climatic contexts. Localised studies, such as [43] provide valuable insights but lack scalability to other regions.

Although stakeholder engagement in energy transitions and the technical evaluation of TES systems have been widely studied, comparative analyses that systematically examine diverse stakeholder perspectives across different climatic contexts are still limited. In particular, while research on battery storage adoption and DSM has proliferated, the integration of user feedback into the iterative design of TES has not been empirically demonstrated. Therefore, this paper investigates how policymakers, engineers, residents, and other stakeholders across four distinct European climates perceive energy storage and flexibility technologies, and how their insights can directly inform both deployment strategies and upstream TES design refinements. By coupling TES with district heating in cold climates and aligning it with demand-side strategies, it advances beyond the barriers identified in earlier research, such as those noted in [8,19].

Demonstration sites in Spain, Austria, Sweden, and Ireland cover span distinct Köppen–Geiger zones, addressing limitations highlighted in [36,44]. The inclusion of diverse stakeholders is a notable feature of the study, involving policymakers, local governments, industries, and end-users to address financial and technical challenges, as noted in the gaps in [34,42]. Validation is supported through structured interviews and multisite pilot projects, addressing implementation gaps noted in [45]. Moreover, customised financial mechanisms complement the findings in [24] to overcome market barriers, while public awareness campaigns align with insights of [26]. In the DSM context, the study advocates participatory governance and financial incentives, resonating with decentralised approaches in [6]. Unlike prior work, which primarily focuses on financing mechanisms [46], governance models [47], or social and institutional adoption barriers [48,49], the current study embeds stakeholder feedback into system design and deployment. By emphasising intermediaries and user-centric strategies, it aims to improve DSM inclusivity and effectiveness between regions and user groups. This holistic framework addresses the gaps in previous research and offers adaptable solutions for sustainable energy transitions worldwide.

The successful implementation and validation of TES systems are based on understanding the application contexts and the needs of diverse stakeholders involved in demonstration sites and living laboratories. These stakeholders include individuals and organisations with expertise in construction, civil engineering, scientific research, technological innovation, social and financial aspects, and legal frameworks. Moreover, the residents of the demonstration sites are integral participants, as their perspectives shape the requirements for TES systems. Stakeholder interviews are conducted to gather knowledge, map beliefs, and explore opinions on energy-related building and renovation issues. These interviews form the basis for comprehensive stakeholder mapping, analysing the influence and interests of key actors. This mapping, in turn, supports the development of a user evaluation model, ensuring TES solutions align with user requirements and expectations.

The aim of this study is to investigate how diverse stakeholders perceive and respond to the implementation of energy storage and flexibility technologies across different European contexts. To address this overarching aim, the research is guided by the following objectives:

- To analyse stakeholder awareness and perceptions of the energy transition, with particular attention to renewable energy, energy efficiency, and emerging technologies such as thermal energy storage (TES) and demand-side management (DSM).
- To identify the perceived barriers and enabling conditions for the adoption of energy storage and flexibility solutions, encompassing technical, economic, informational, and behavioural dimensions.
- To examine how local contexts and stakeholder roles (e.g., residents, policymakers, engineers) shape attitudes toward energy innovation across four distinct European pilot sites.
- To assess the potential for stakeholder engagement to inform system design, particularly through the integration of user feedback into the development of TES systems and DSM tools.
- To generate evidence-based insights for future policy and implementation strategies, with an emphasis on enhancing the scalability, usability, and acceptability of energy storage technologies across diverse settings.

This study advances the literature by integrating TES, DSM, and energy efficiency within a unified, stakeholder-informed framework, empirically validated through pilot projects conducted in Spain, Austria, Sweden, and Ireland. It addresses critical gaps by coupling TES with renewable energy systems and by systematically analysing the technical, economic, and social barriers to adoption. Moreover, it offers scalable, context-sensitive solutions, including hybrid service models and participatory design approaches, that bridge the divide between technological innovation and societal acceptance. The findings provide strategic recommendations for policymakers, researchers, and industry practitioners, thereby contributing to the development of cost-effective, inclusive, and sustainable energy transition pathways across heterogeneous European contexts.

2. Methodology

A qualitative methodology based on semi-structured interviews was employed to explore stakeholder perspectives on energy transition across four European demonstration sites. This approach enabled the collection of context-specific insights from a diverse range of actors, including policymakers, technical experts, and community representatives. The design prioritised thematic coherence, cross-site comparability, and methodological transparency. The following subsections outline the interview structure, sampling strategy, analytical procedures, stakeholder composition, and ethical safeguards.

2.1. Structure and thematic focus

The stakeholder interviews were structured into twelve distinct sections, each designed to address a specific theme aligned with the overall research objectives. The questionnaire was collaboratively developed by an international, multidisciplinary team with extensive expertise in energy systems and stakeholder engagement. This collaborative approach ensured that the interview content was both comprehensive and pertinent to the project's scope. A semi-structured interview format was adopted to enable depth and flexibility in qualitative data collection. The questionnaire comprised twenty open-ended questions organised into five overarching thematic areas: general energy issues, energy efficiency, energy technologies, energy storage, and DR solutions. Within each section, the questions were introduced with a brief rationale, and were frequently supplemented by prompts, clarifications, and follow-up questions, thereby aiding interviewers in addressing complex or technical subjects. The complete set of questions is detailed in the appendix (Table A.2), and the relationship between the questionnaire and the five thematic areas is illustrated in Fig. 2. This methodological design facilitated the exploration of both predefined and emergent themes, enabling interviewees to elaborate on matters they deemed significant. Interviewers were also encouraged to explore topics arising naturally in the conversation, thereby enhancing the depth and contextual richness of the data collected.

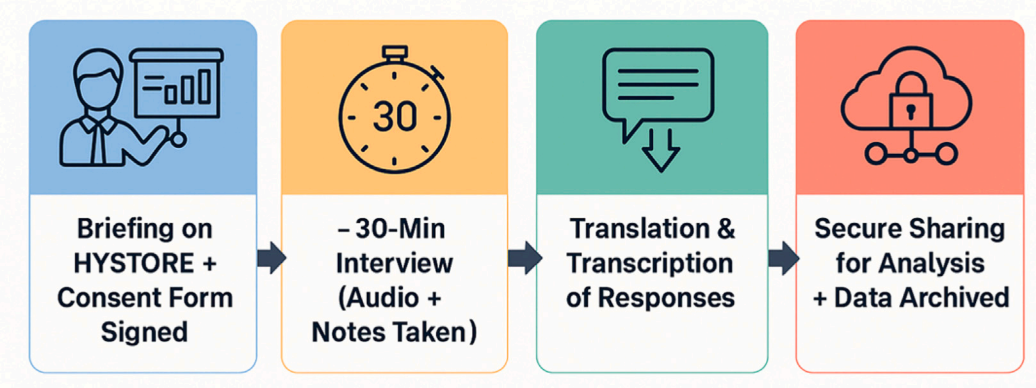


Fig. 1. Overview of the stakeholder interview workflow.

2.2. Data collection procedures

Interviews were conducted either in person or online, depending on logistical constraints and the preferences of participants. Each demonstration site leader was responsible for identifying six to eight interviewees with a direct connection to the relevant demonstration site, thereby ensuring that the data collected was grounded in practical, context-specific experiences. Interviews typically lasted between 30 and 40 min, providing adequate time for comprehensive discussion of the questions and any clarifications requested by participants. All interviews were audio-recorded following informed consent, and interviewers concurrently took detailed notes to capture contextual subtleties. Verbatim transcripts were produced by integrating the audio recordings and written notes. These transcripts underwent participant validation – also referred to as member checking – whereby each interviewee reviewed and approved their transcript to ensure accuracy and reduce the potential for misinterpretation. Anonymisation was carried out at the transcription stage, with any identifying information removed prior to secure storage of the data in a restricted-access repository.

2.3. Analytical approach and data management

Thematic analysis of the interviews was conducted using a predefined coding framework corresponding to the considered research themes, including energy transition, efficiency, storage technologies, and DR. Although no formal qualitative analysis software was employed, the data was systematically organised using Excel spreadsheets, which facilitated both thematic coding and structured cross-case analysis. The analysis drew on a range of comparative tools, including summary tables, quantitative charts (such as bar and pie charts), word clouds, geographic maps, and cross-stakeholder comparisons. This multi-format synthesis enabled consistent comparisons of perspectives across different stakeholder groups and national contexts, thereby enhancing internal analytical robustness. While formal coding software was not utilised, the thematic structure ensured consistency throughout the analytical process. To ensure methodological clarity and facilitate future replication, the associated table (Table A.4) has been included in the appendix. This table outlines procedures for stakeholder selection, interview design, ethical safeguards, data transcription, anonymisation, coding, and thematic analysis. It provides a transparent and replicable framework for conducting similar qualitative studies within multi-site demonstration contexts. Finally, the visual workflow diagram in Fig. 1 illustrates the standardised data collection and processing pathway, covering briefing and consent, the interview session, transcription and translation, and secure archiving.

2.4. Sampling methodology

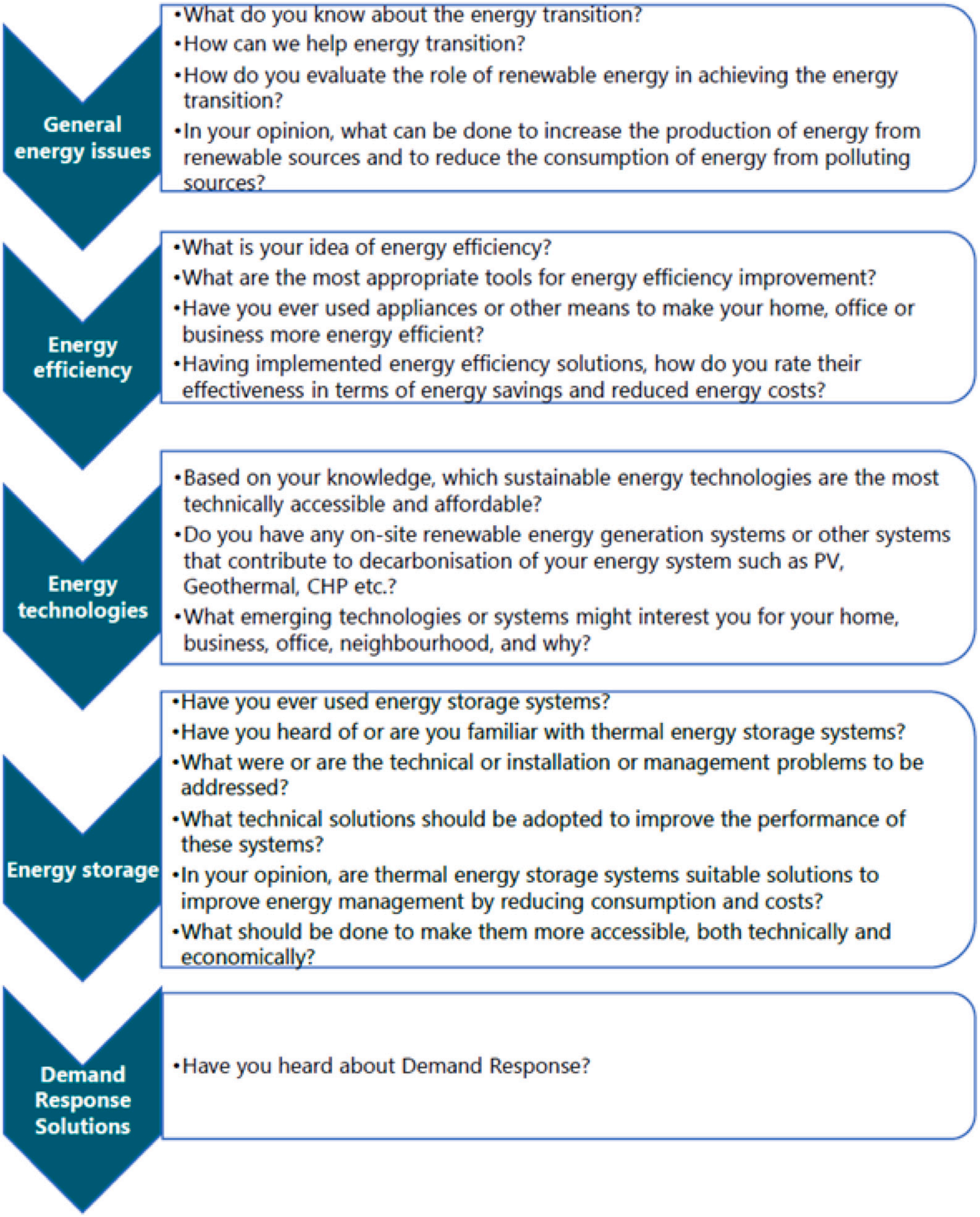
Stakeholders were selected using a purposive sampling strategy conducted in close collaboration with demonstration site leaders. The initial pool of participants was identified through recommendations from site representatives, followed by snowball sampling to include additional individuals with relevant institutional or social connections. The primary criterion for inclusion was a demonstrable, direct association with one of the HYSTORE pilot sites, either through professional roles or local engagement. No fixed exclusion criteria, such as minimum years of experience, were applied. However, all selected participants were expected to hold responsibilities, knowledge, or insights pertinent to energy systems, storage technologies, or demonstration site operations. The sampling strategy was explicitly designed to support the subsequent participatory phase of the project, ensuring that interviewees could contribute meaningfully to device co-development.

2.5. Stakeholder composition and diversity

The interviewees represented a broad and diverse array of stakeholder categories. These included decision-makers such as local politicians, mayors, municipal authorities, university deans, managers — including department heads and school principals, business actors such as entrepreneurs, suppliers, utility representatives, professionals such as engineers, architects, and financial advisors. Additional participants comprised technical staff and site workers, residents and local users including homeowners, students, and shopkeepers, as well as representatives from third-sector organisations such as charities, social enterprises, and housing associations. Efforts were made to ensure diversity with respect to role, institutional affiliation, technical expertise, gender, and age, thereby enhancing the representativeness and inclusivity of the sample. Geographic balance was maintained across the demonstration countries, and although the study aimed for maximum inclusivity, certain limitations were acknowledged. These include the underrepresentation of disengaged citizens, national-level regulators, and large energy firms, as well as variability introduced using different languages and mixed interview formats.

2.6. Ethical considerations

The interviews were conducted in accordance with a standardised protocol (Table A.4), which detailed ethical safeguards, interviewer conduct, and procedures for adapting the interview guide to local contexts. Translation and cultural adaptation were employed to ensure that questions were contextually appropriate and comprehensible to a diverse stakeholder base. Audio recording and data processing were undertaken only after informed consent had been explicitly obtained from each participant.



General energy issues

- What do you know about the energy transition?
- How can we help energy transition?
- How do you evaluate the role of renewable energy in achieving the energy transition?
- In your opinion, what can be done to increase the production of energy from renewable sources and to reduce the consumption of energy from polluting sources?

Energy efficiency

- What is your idea of energy efficiency?
- What are the most appropriate tools for energy efficiency improvement?
- Have you ever used appliances or other means to make your home, office or business more energy efficient?
- Having implemented energy efficiency solutions, how do you rate their effectiveness in terms of energy savings and reduced energy costs?

Energy technologies

- Based on your knowledge, which sustainable energy technologies are the most technically accessible and affordable?
- Do you have any on-site renewable energy generation systems or other systems that contribute to decarbonisation of your energy system such as PV, Geothermal, CHP etc.?
- What emerging technologies or systems might interest you for your home, business, office, neighbourhood, and why?

Energy storage

- Have you ever used energy storage systems?
- Have you heard of or are you familiar with thermal energy storage systems?
- What were or are the technical or installation or management problems to be addressed?
- What technical solutions should be adopted to improve the performance of these systems?
- In your opinion, are thermal energy storage systems suitable solutions to improve energy management by reducing consumption and costs?
- What should be done to make them more accessible, both technically and economically?

Demand Response Solutions

- Have you heard about Demand Response?

Fig. 2. Structure of the questionnaire.

3. Interview response analysis

In this section, the responses to the distributed questions are systematically reviewed, and opinions requiring further examination are highlighted for additional analysis. A total of 23 interviews were obtained from the four demonstration sites.

3.1. Stakeholder demographic information

A diverse set of stakeholder groups was interviewed, and their territorial and gender information are depicted in Fig. 3. Interview responses were obtained from Spain, Ireland, Austria, and Sweden. The underrepresentation of women reflects broader gender imbalances in the engineering sector, rather than indicating any lack of commitment to diversity and inclusion. Most of the stakeholders have completed their university education (87%) (Fig. 5).

The stakeholder types covered are illustrated in the word cloud of Fig. 4. The frequency of stakeholder categories highlights the prominence of managing directors, academics, and academic researchers, indicating that individuals with significant decision-making authority and specialised knowledge were primarily involved. The inclusion of other stakeholders, such as technical employees, project managers, and representatives from city councils, was intended to incorporate a broader range of perspectives across technical, managerial, and policy dimensions. A total of five interview results were received from the Irish pilot partner, primarily involving academics, with three respondents identified as internal stakeholders and two as external stakeholders, all of whom were professionals in energy-related fields. Meanwhile, six interview results were obtained from the Spanish pilot partner, encompassing the roles of technical director, architect, project manager, and IT developer, with two participants serving as internal stakeholders and four as external stakeholders, all of whom worked at the demonstration site. Furthermore, six interview results were provided by the Swedish pilot partner, which included feedback from an academic researcher

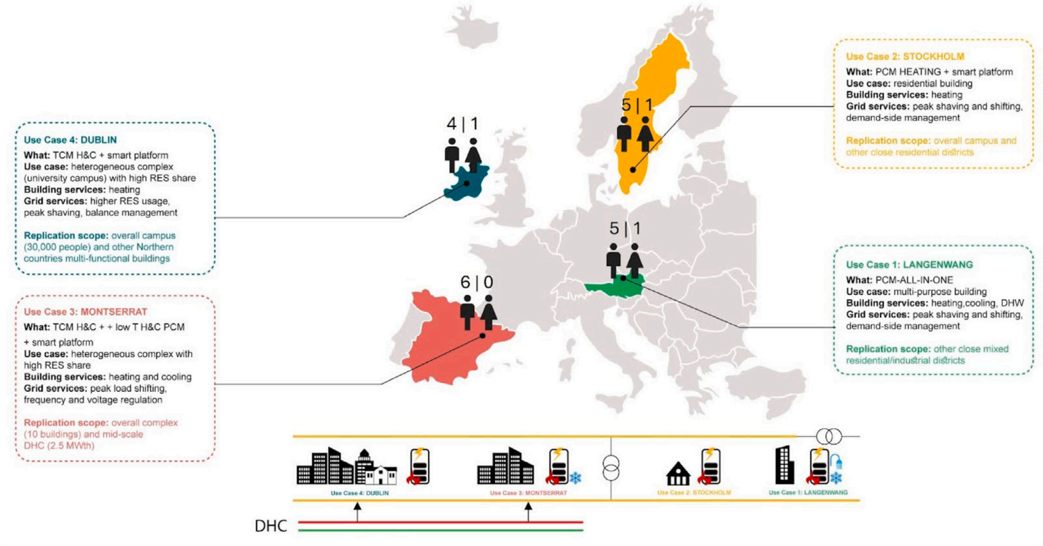


Fig. 3. The territorial distribution of stakeholder participants, including total numbers and gender composition.

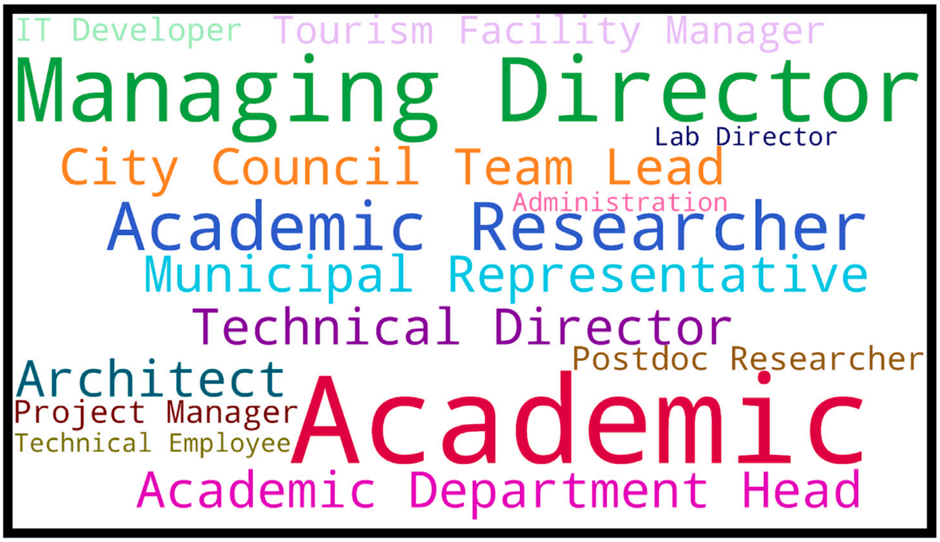


Fig. 4. Word cloud of the stakeholder categories.

and a director. Lastly, six additional interview results were collected from the Austrian pilot partner, representing a municipality lead, a managing director, a technical employee, and a district administrative authority. Table A.3 provides a summary of the stakeholder categories engaged across the four demonstration countries — Spain, Austria, Sweden, and Ireland.

3.2. *General energy issues*

This set of questions was formulated to assess respondent knowledge, opinions, and positions on energy issues, with a particular emphasis on the energy transition.

3.2.1. *What do you know about the energy transition?*

The stakeholders were invited to assess their awareness of the pressing issue of energy transition. Among the 23 individuals interviewed, all stakeholders unanimously understood the necessity of energy transition. Stakeholders primarily acquired this knowledge through formal education and professional networks. Furthermore, all participants demonstrated awareness of the role of energy transition in reducing GHG emissions and recognised the importance of renewable energy in this context. Their responses indicated that the integration of RES, improvements in energy efficiency, and the optimisation of energy demand are pivotal strategies for facilitating the energy transition. The significance of individual responsibility in supporting this process was also emphasised.

The analysis of stakeholder responses revealed a growing societal awareness of the detrimental impacts of fossil fuel consumption, particularly in relation to global warming, the energy crisis, climate change, and implications for future generations. However, several challenges to the implementation of energy transition were highlighted. These included the absence of adequate tools, gaps in political and economic policies, and insufficient information dissemination. A minority of stakeholders demonstrated awareness of global and European Union targets aimed at transitioning from fossil fuels to RES. A minority of stakeholders referenced global and EU targets, such as the EU's plan to transition to clean energy by 2030 and alignment with the COP agenda, EU legislation, and the UN Sustainable Development Goals.

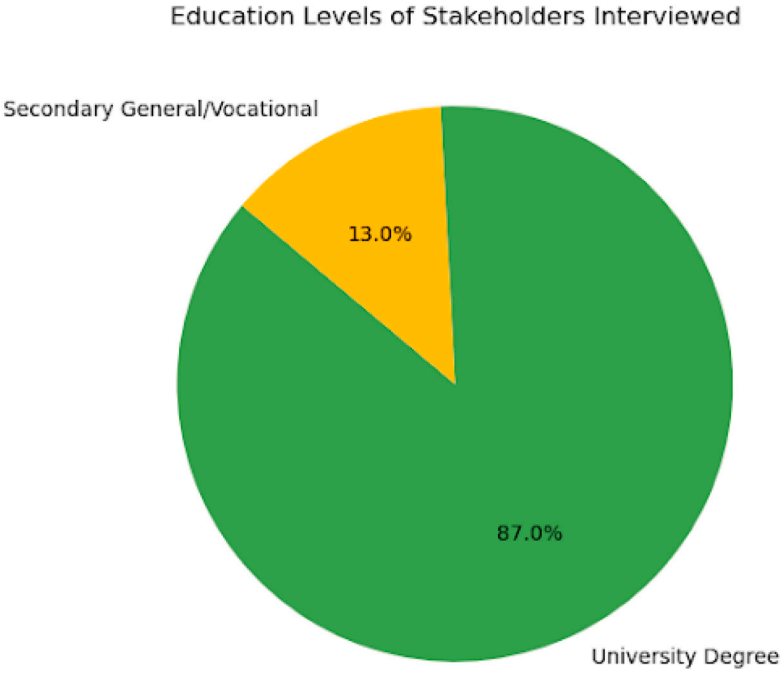


Fig. 5. Educational qualification of the respondents.

3.2.2. How can we help energy transition?

Academic researchers highlighted their roles in developing innovative, energy-efficient, and sustainable technologies. They also emphasised the importance of disseminating research findings to students and the public and advancing software solutions to integrate and optimise renewable energy systems. At the personal level, stakeholders identified several actions to support the energy transition, including reducing energy demand, participating in DSM, and adopting energy-efficient practices. They also suggested promoting teleworking and cycling, replacing carbon-intensive equipment with energy-efficient alternatives, and installing renewable energy solutions in homes and workplaces.

Policy makers and local authorities proposed measures to drive the transition at policy and community levels. These included revising energy policies, introducing behavioural change initiatives, and reallocating land for renewable energy projects. Additional recommendations involved transitioning to district heating systems, aligning energy suppliers with consumer needs, and supporting solar and wind projects at the community level. Policy makers also stressed the importance of financial incentives to encourage stakeholder participation and educating property owners on implementing renewable energy solutions in buildings.

3.2.3. How do you evaluate the role of renewable energy in achieving the energy transition?

The stakeholders emphasised the central role of renewable energy in the energy transition, highlighting its sustainability, elimination of GHG emissions, and environmental benefits. They pointed out that the carbon footprint of renewable energy—both embedded and operational—is significantly lower than that of fossil fuels. This reduced footprint is viewed as essential for achieving energy independence and advancing the energy transition. However, concerns about the security of supply linked to RES were raised. Stakeholders suggested that these limitations could be addressed through effective energy storage solutions. Additionally, they stressed the importance of consumer engagement in facilitating this transition. Several advantages of renewable energy were identified, including reduced GHG emissions, enhanced energy security, sustainability, improved energy access, grid stability, lower costs, long-term viability, and support for energy independence. Despite these benefits, stakeholders acknowledged several challenges in implementation. Key obstacles included energy storage limitations, outdated infrastructure, the need for grid upgrades, insufficient consumer awareness, and economic and political barriers.

To address these issues, stakeholders offered various insights. One highlighted the necessity of renewable energy as a fundamental pillar of the energy transition, noting that efficiency improvements alone will not be sufficient to meet the anticipated global rise in energy demand, particularly in underdeveloped countries. They highlighted the importance of adopting solutions with minimal environmental impact and suggested that emissions should carry a financial penalty to reflect their true cost. Another stakeholder emphasised that the success of the energy transition depends on the widespread adoption and distribution of RES, alongside efforts to overcome infrastructure and policy challenges.

3.2.4. How can we boost renewable energy production and reduce reliance on polluting sources?

The stakeholders emphasised that a multi-faceted approach is essential to increasing energy production from RES. This approach should include government policies, technological advancements, individual actions, investment in research and development, cost reductions, and improved energy storage solutions. Several key strategies were highlighted to advance renewable energy adoption. Stakeholders proposed actively involving property owners and building managers in the energy transition to promote grassroots-level integration of renewable energy. Ensuring that renewable energy technologies are accessible to end-users was considered crucial, alongside the introduction of clear incentives and financial mechanisms. These were considered as vital not only to support environmental sustainability but also to drive economic growth and business development.

Investment in research and development was particularly emphasised to improve the efficiency and reliability of RES, thereby building user confidence. Legislative support and cost-effective solutions were also identified as critical accelerators of adoption. Additionally, stakeholders underscored the importance of expediting planning processes, leveraging cutting-edge technologies, and prioritising energy efficiency to optimise implementation efforts. Political and social consensus was viewed as a cornerstone for successfully implementing renewable energy projects. Infrastructure development, particularly the expansion of the grid to accommodate increased renewable energy generation, was highlighted as a pressing need. Finally, stakeholders recommended prioritising renewable energy during system upgrades or refurbishments to ensure a seamless transition to a sustainable energy future.

3.3. Energy efficiency

The respondents' knowledge and familiarity with energy issues were explored, beginning with the general topic of energy efficiency. This included determining their awareness of technical solutions and whether they had adopted structural changes, equipment upgrades, or behavioural modifications (e.g., monitoring consumption) to improve efficiency.

3.3.1. What is your idea of energy efficiency?

The stakeholders collectively demonstrated a robust understanding of energy efficiency, primarily stemming from their professional experiences and educational backgrounds. They emphasised its critical role in advancing the energy transition by significantly reducing energy consumption and waste. In addition to these direct benefits, they highlighted broader advantages, including the reduction of GHG emissions, improved public health, and reduced environmental pollution, underscoring the multi-faceted impact of energy efficiency on society and the environment. A particularly insightful observation came from one stakeholder, who highlighted the inefficiency of fossil fuel-based energy generation, where substantial energy is lost during conversion and distribution. This prompted the suggestion that distributed energy generation could be a viable solution to minimise these losses, thereby enhancing the efficiency of energy systems as a whole. The group also proposed practical measures to improve energy efficiency. These included simple actions such as turning off unnecessary devices and lights, ensuring equipment is utilised as intended, and replacing outdated appliances with energy-efficient alternatives. They further recommended optimising heating system usage, improving communication between system components, reducing waste, and adopting consumption habits aimed at achieving higher efficiency.

The stakeholders recognised numerous benefits associated with energy efficiency. Beyond mitigating environmental impacts, they noted that it enhances energy security, lowers operational costs, fosters economic growth, and improves comfort and productivity. They also stressed its potential to optimise existing infrastructure, reduce energy demand and peak loads, conserve resources, and lower energy bills, ultimately contributing to a more sustainable and balanced energy ecosystem. To maximise these benefits, the stakeholders advocated for societal shifts in consumption behaviour, encouraging a mindset that prioritises necessity over excess. They called for improved communication tools within energy systems, targeted staff training programmes, and greater efforts to educate property owners on the importance and implementation of energy-efficient practices. Specific perspectives added further depth to the discussion. One participant stressed the importance of designing and operating energy systems in alignment with their intended use, highlighting that inefficient default settings often result in excessive energy consumption. This could be addressed through corrective measures, such as optimising heating systems for functionality and efficiency. Another participant offered a redefinition of energy efficiency, proposing that it should not merely reflect the ratio of output to input but should focus on achieving desired outputs with the minimum energy usage and the lowest possible carbon emissions. This approach, they argued, aligns better with sustainability goals and reflects the true essence of energy efficiency in the context of the energy transition.

3.3.2. What are the most appropriate tools for energy efficiency improvement?

The respondents provided an array of suggestions for tools and strategies to improve energy efficiency, showcasing the varied approaches needed to address this complex issue. Practical measures were a key focus, with stakeholders advocating for actions such as energy-saving practices, turning off unnecessary energy-consuming devices, and making judicious use of heating systems. Training users to adopt efficient behaviours and operating equipment within optimal specifications were also highlighted as vital steps. Renovating buildings based on detailed building physics calculations was recommended to improve energy performance, alongside replacing inefficient equipment and encouraging innovation in products and system optimisation. Advanced tools and technologies were frequently suggested, including energy auditing and management systems, smart grid technologies, and the Internet of Things for real-time monitoring and optimisation. Monitoring devices, internet and technology applications, and energy management platforms were considered as essential for effective energy control. Educational campaigns, particularly through mass media, were proposed as a means to foster energy-conscious behaviours across a wide audience. Stakeholders also stressed the importance of involving multidisciplinary experts in the design, installation, and maintenance of energy systems, recognising that such expertise is crucial for operational efficiency and effectiveness.

Investment in research and the adoption of a multidisciplinary approach were viewed as critical for developing and implementing advanced energy-efficient technologies. Proposals included the creation of tools such as a carbon calculator to help citizens estimate their life cycle carbon emissions and increasing property owners' and facility managers' awareness of mitigation measures. Respondents also called for innovation in technologies capable of operating under extended technical constraints. The majority of stakeholders reported acquiring their knowledge of energy-efficient technologies and systems through professional networks, while a smaller number attributed their understanding to self-directed learning.

Behavioural changes were identified as a pivotal factor in achieving energy efficiency, although respondents acknowledged significant challenges in this area. One noted that societal norms prioritising high efficiency and consumption over sufficiency create barriers to change. Another pointed to sectors such as transportation and heating as particularly challenging due to the high number of decision-makers and their varying levels of agency. For instance, individual homeowners and transport users often lack the knowledge or confidence to adopt low-carbon solutions. Respondents also highlighted the difficulty of sustaining long-term behavioural changes, as individuals tend to revert to previous habits. While user education on energy efficiency was acknowledged as critical, it was also identified as highly challenging due to difficulties in effectively reaching all end-users, the time-intensive nature of sustained engagement, and the inherent unpredictability of user behaviour. Even with advanced analytical methods such as statistical modelling and machine learning, the complexity of influencing widespread behavioural change remains a significant obstacle.

3.3.3. Have you ever used appliances or other means to make your home, office or business more energy efficient?

The question aimed to explore the tools and measures stakeholders employ to improve energy efficiency in their homes, offices, or businesses. Responses revealed widespread commitment among the participants, with 19 of the 23 interviewed reporting various energy efficiency initiatives. These efforts were motivated by a combination of personal interest, economic considerations, and environmental concerns, demonstrating a strong alignment with the objectives of the energy transition.

The measures implemented were diverse, reflecting a range of approaches. Stakeholders reported adopting electric vehicles and alternative mobility options such as cycling, installing solar thermal systems for domestic hot water, and improving home insulation. Many had replaced outdated appliances with energy-efficient models, undertaken home renovations incorporating advanced insulation techniques, and installed energy-efficient windows and heating systems. Additionally, efforts were made to optimise energy consumption through user behaviour adjustments and employee training programmes. Some stakeholders highlighted the importance of basing renovations on detailed building physics calculations to maximise energy performance.

Participants also embraced advanced technologies such as telemetry systems for energy monitoring, aerothermal systems for domestic hot water and space heating, and heat pumps (HPs) powered by solar PV systems. Lighting upgrades, including the replacement of traditional bulbs with LEDs and the introduction of dimming systems in office spaces, were common. Monitoring systems and smart tools such as mobile apps for remote energy management and building management systems were frequently mentioned as essential for achieving greater efficiency. Stakeholders also prioritised purchasing equipment with high energy efficiency ratings, such as Class A appliances, and adopting energy-conscious behaviours. In Sweden, stakeholders noted the prevalence of HPs in rural areas, driven by government incentives supporting their installation alongside solar PV systems. However, several respondents expressed frustration over systemic barriers, such as a shortage of registered contractors, which hindered access to these incentives. This issue limits the effectiveness of government programmes, leaving many unable to fully benefit from available support.

The role of data measurement and communication systems was consistently emphasised. For instance, one participant noted that installing home monitoring devices providing real-time energy consumption data significantly raised household awareness and encouraged more efficient energy use. Another discussed how building management systems enabled detailed monitoring of energy, water, and gas consumption across building sections, helping to control costs and improve performance. While acknowledging that not all buildings are equipped with such tools, respondents highlighted ongoing renovations aimed at integrating these systems to enhance efficiency. The increasing complexity of modern infrastructure was cited as a challenge, requiring tools capable of processing and analysing large volumes of data effectively.

Stakeholders identified various factors driving the adoption of energy efficiency tools, including equipment energy ratings, cost, life expectancy, potential energy savings, government incentives, and organisational energy management policies. Beyond these practical drivers, environmental concerns, personal interest, aesthetic preferences, and enthusiasm for technological innovations were also significant motivators. Despite their enthusiasm for energy efficiency, many respondents viewed government incentives as limited in impact. A lack of registered contractors was repeatedly identified as a barrier to accessing these programmes, prompting calls for policy reforms to address this issue. While some participants had benefited from incentives, they noted that the support often fell short, underscoring the requirement for improved mechanisms to ensure these programmes meaningfully assist stakeholders in adopting energy-efficient solutions.

3.3.4. How do you rate the effectiveness of energy efficiency solutions in saving energy and reducing costs?

Stakeholders showed strong support for the implementation of energy efficiency measures, emphasising notable reductions in energy consumption alongside corresponding financial savings. Beyond these immediate benefits, stakeholders also emphasised the broader advantages of energy efficiency improvements, including enhanced habitability, greater comfort, better health outcomes, and an overall improved quality of life. These outcomes reflect the multifaceted impact of energy efficiency measures, extending beyond cost savings to encompass tangible improvements in living conditions.

However, stakeholders also stressed the importance of ensuring the long-term effectiveness and sustainability of energy efficiency solutions. One respondent noted that the effectiveness of such measures depends on various factors, such as the specific solutions implemented, the scale of their application, existing energy consumption patterns, and the commitment to ongoing maintenance and monitoring. Without adequate attention to these aspects, the potential benefits of energy efficiency initiatives may not be fully realised over time. Another stakeholder highlighted the need for a comprehensive and long-term perspective when evaluating energy efficiency solutions. They pointed out that investment, installation, operation, and maintenance costs must all be carefully considered to make a fair assessment of the viability and sustainability of these measures.

3.4. Energy technologies

The scope of the following questions is to assess the respondents' level of knowledge and familiarity with energy technologies, with a particular focus on environmentally friendly solutions. Additionally, the inquiry aims to determine whether the respondents are currently utilising a renewable energy system or have plans to adopt one in the future.

3.4.1. Which sustainable energy technologies are the most technically accessible and affordable?

The stakeholders demonstrated familiarity with and implementation of a variety of energy technologies, including solar PVs, solar thermal collectors, electric vehicles, LED lighting, HPs, batteries, geothermal energy, biomass heating, and wind energy. Among these, solar PV was identified as the most affordable, accessible, and easily installable sustainable solution. Specifically, the data revealed that 66% of stakeholders considered solar PV to be a potential low-carbon energy technology. HPs were the second most familiar energy technology among stakeholders, with 15 out of 23 participants aware of their use for space heating, cooling, and domestic hot water requirements. While HPs were recognised as effective, stakeholders noted their higher upfront costs and shorter lifespans compared to conventional boilers. Awareness of HP variants – air source, water source, and ground source – was evident, with air source HPs identified as the more economical option due to the additional capital costs associated with deep drilling for ground source systems. HPs were particularly popular in Sweden and Austria, where incentives have facilitated their adoption. In Sweden, the integration of HPs with exhaust and supply air ventilation with heat recovery systems was noted as a common practice. These systems were promoted for their ability to supply large quantities of ventilation air and maintain high performance regardless of weather conditions [50].

LED lighting was another widely recognised technology, with stakeholders acknowledging the associated energy efficiency benefits. Electric vehicles were also familiar, though stakeholders expressed concerns about insufficient charging infrastructure and the high costs for private individuals. They also questioned the associated sustainability, indicating that broader infrastructural and systemic improvements are required. Wind energy was recognised as a low-carbon technology, but stakeholders noted that the placement of wind turbines is often constrained by regulations, limiting their widespread adoption. Other familiar technologies included biomass heating, geothermal energy, batteries, aerothermal installations for heating, and hydropower.

Several stakeholder-specific insights added depth to the discussion. For instance, solar thermal water heating, despite being a simple and well-established technology, was reported to face challenges due to a lack of proper maintenance. Stakeholders observed that while solar thermal panels are effective and useful when maintained, they often fail in smaller buildings where maintenance practices are limited. This challenge arises because maintenance is frequently perceived as an expense rather than an investment in the longevity of the technology. Stakeholders also highlighted the importance of tailoring energy technology choices to specific site conditions. They emphasised that the most appropriate and efficient technology should be selected based on a

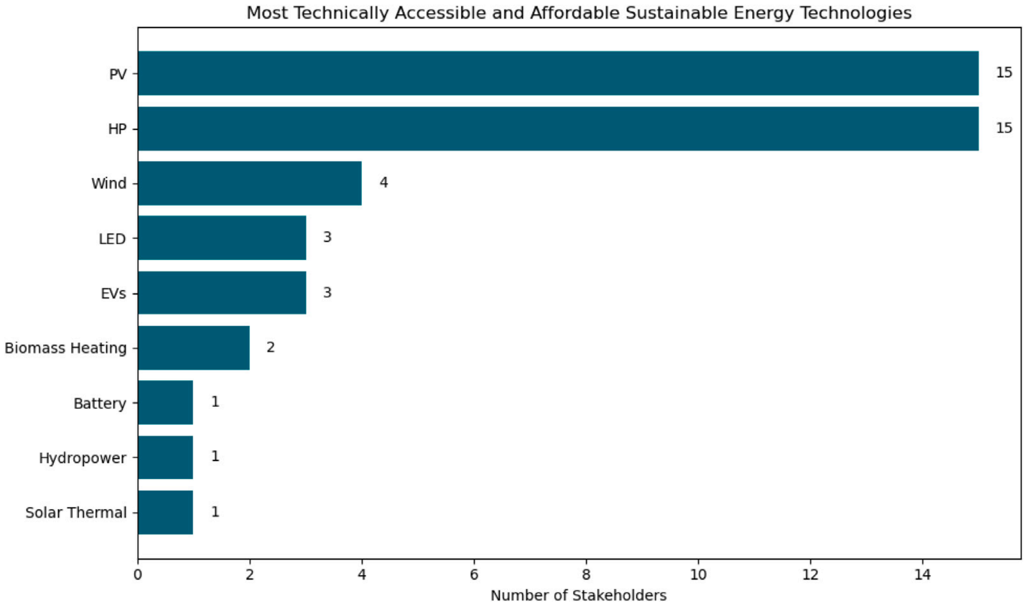


Fig. 6. Stakeholders response on sustainable energy technologies that are technically accessible and affordable.

detailed evaluation of the site, ensuring that the solution aligns with the specific requirements and conditions of the location. Additionally, the implementation of a fabric upgrade programme, focusing on improving the energy efficiency of social housing stock, was highlighted as an effective strategy for enhancing building performance [51]. The stakeholder perceptions of the most technically accessible and affordable sustainable energy technologies are summarised in Fig. 6.

3.4.2. Do you have on-site renewable energy systems or other decarbonisation technologies like PV, geothermal, or CHP?

The technologies commonly installed by stakeholders at their homes or workplaces to help decarbonise energy systems include solar PV, HPs, geothermal heating, CHP systems, and biomass district heating. Among these, solar PV was the most frequently installed, with 14 out of 23 participants reporting installations at their residences or workplaces. Five stakeholders had HPs installed in their homes, while biomass heating emerged as another widely implemented technology, following HPs and solar PV. Fig. 7 illustrates the number of the interviewed stakeholders that implemented on-site renewable energy technologies. The increased adoption of solar PV reflects its accessibility and popularity among stakeholders. Stakeholders from Sweden noted that solar PV, HPs, and biomass heating are particularly common in their country. Other technologies implemented included geothermal heating, aerothermal systems, district heating, and LED lighting. However, storage solutions were rarely found among stakeholder installations. Only one participant reported having installed a solar thermal hot water system, suggesting a possible decline in its popularity. A specific response highlighted the high investment cost associated with replacing older heating solutions as a significant challenge. For instance, one stakeholder stated: *"Not in my house, it is an old flat with a gas boiler. The investment cost to make the change is too high, and the volume occupied by the new technology is too large for small flats"*.

3.4.3. What emerging technologies or systems might interest you for your home, business, office, neighbourhood, and why?

The responses to this question align closely with findings from earlier discussions, particularly regarding the strong interest in the installation of solar PV systems. This interest is largely driven by the economic and sustainable benefits that PV offers, with 11 participants expressing an interest to install PV systems at their homes or offices. HPs also garnered significant interest, particularly as replacements for gas or oil heating systems. Among these, air source HPs were specifically mentioned for their cost-effectiveness. At the community level, stakeholders showed interest in technologies such as biomass district heating, neighbourhood-scale battery storage, and wind energy conversion systems. Additionally, there is a growing recognition of the potential of both electrical and TES solutions, with Swedish interviewees demonstrating particular interest in storage technologies. In contrast, Spanish stakeholders displayed limited interest in storage solutions, indicating a need for extensive dissemination efforts to raise awareness and understanding in this area. Specific interest was also noted in TES for building heating applications. Stakeholders further expressed interest in non-fossil fuel vehicles, although current financial challenges were identified as a barrier to adoption. Exceptional responses included hydrogen boilers, smart grids, and smart home energy management systems.

Some specific stakeholder opinions provided further insights into the factors influencing interest and feasibility. One respondent highlighted the potential benefits of smart grid systems, emphasising their ability to integrate RES and enhance grid resilience and reliability. Another pointed out the challenges posed by aesthetic regulations and community-based decision-making in certain areas, such as Barcelona, which could complicate the installation of technologies such as PV systems. For rural areas, such as village houses, installation feasibility was seen as more flexible but still dependent on regulations. A recurring theme in the responses was the importance of effective integration and coordination among existing systems. Stakeholders noted that while heating, cooling, and storage technologies are generally mature and convenient, increased coordination between units in buildings or communities is required for optimal performance. The quotes also reflect the need for systemic coordination and policy incentives: *"We need to first make the existing systems work together better and develop sound business models and make incentives consistent"*.

3.5. Energy storage

This section explores a topic closely aligned with the objectives of the HYSTORE project. The discussion begins with an assessment of respondents' knowledge and familiarity with energy storage systems, before gradually transitioning to more specific inquiries about TES systems. Regarding TES, the focus encompasses both respondents with

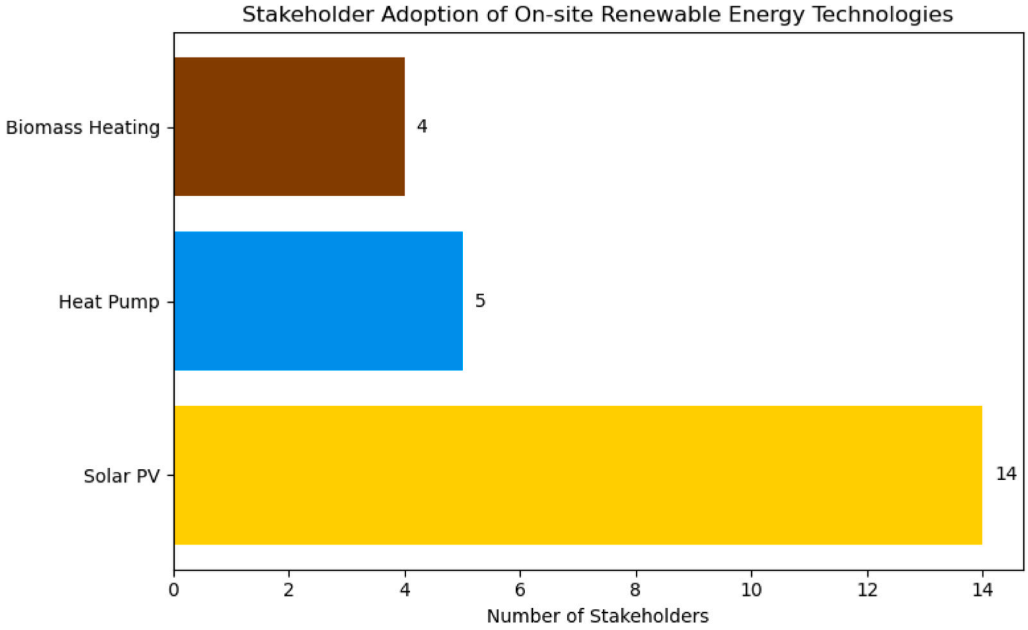


Fig. 7. On-site renewable energy technologies implemented by the interviewed stakeholders.

no prior experience of these systems and those who have actively used them. For individuals with experience, the questions are designed to elicit insights into their practical utilisation of TES devices, including the challenges they encountered, the benefits they observed, and their overall impressions of the technology. This structured approach aims to develop a comprehensive understanding of stakeholder perspectives on energy storage and TES technologies.

3.5.1. Have you ever used energy storage systems?

The stakeholders were asked about their use of energy storage technologies. Of the 23 individuals interviewed (with one not responding), 16 reported having utilised such solutions. The most widely used option was hot water tanks, favoured by 14 respondents due to their accessibility and cost-effectiveness. Batteries were the second most popular choice, implemented by eight stakeholders, particularly for their compatibility with PV systems. Fig. 8 shows the levels of stakeholder experience with energy storage systems at the sites, separated into users and non-users. However, concerns about batteries were also raised, with stakeholders citing issues such as limited lifespan and performance degradation over time. Another technology noted was the use of solar diverters, which redirect excess power from solar PV-battery systems to immersion heaters in water storage tanks, thereby enhancing the energy efficiency and self-sufficiency of PV systems. Advanced concepts such as latent heat storage using PCM were also mentioned, though their application remains limited to research settings at present.

For stakeholders who had not implemented energy storage technologies, the primary reasons included high costs, insufficient space, limited information, concerns about the lifespan of storage systems, and the use of toxic materials in their construction. These barriers highlight critical areas that must be addressed as part of the HYSTORE project to ensure the successful adoption of its products. Several specific stakeholder opinions warrant attention. One respondent expressed a lack of awareness about the benefits of energy storage systems for residential use, indicating the need for improved dissemination of information. Another stakeholder, intrigued by the potential of PCM storage, highlighted a lack of clarity about its environmental impact, particularly regarding the recyclability of materials used in electric batteries. Concerns were also raised about the durability of electric batteries, with one stakeholder noting that their batteries lost significant capacity within seven to eight years, ultimately leading them to switch to a virtual cloud system.

At the community level, high investment costs and limited returns from batteries further hindered their adoption. The popularity of hot water tanks was constrained by questions about the advantages of more advanced thermal storage solutions, such as PCM or TCM storage. On the issue of trust and maturity, several respondents highlighted skepticism towards newer TES technologies, favouring traditional systems. One interviewee remarked: *“Water tanks. But there is a lot of research work going on for PCM storage, TCM storage etc., but I don’t believe they will be on the market very soon... if we can use a simple water tank, what are the unique aspects that other thermal storage should be considered instead of a tank?”.*

3.5.2. Have you heard of or are you familiar with thermal energy storage systems?

Out of the 21 stakeholders who responded, 18 indicated familiarity with the concept of TES, particularly in relation to hot water storage tanks. This familiarity was largely attributed to their professional backgrounds, with many stakeholders expressing an interest in further exploring the topic in the future. Their current interest in utilising TES appears to be driven by its convenience. Several opinions provide valuable insights into stakeholder perspectives on TES. One respondent with limited familiarity highlighted the challenges of scheduling storage heaters to achieve desired thermal comfort levels. Another respondent noted that TES solutions are not widely disclosed or commercially available, which limits their awareness and accessibility. A third stakeholder expressed an interest in learning more about TES but emphasised the importance of presenting the information in a manner that is accessible to non-experts. Lastly, another respondent pointed out that emerging technologies, such as PCM, are perceived as insufficiently mature for effective integration into existing heating systems.

3.5.3. What were or are the technical or installation or management problems to be addressed?

Stakeholders have mentioned a long list of problems that need to be addressed for the implementation of a TES system. These include technical problems such as heat loss, the requirement for a complex control system, challenges in maintaining the desired temperature within TES systems, and the absence of a commercial product. Installation-related issues include space availability and the need for training of installers

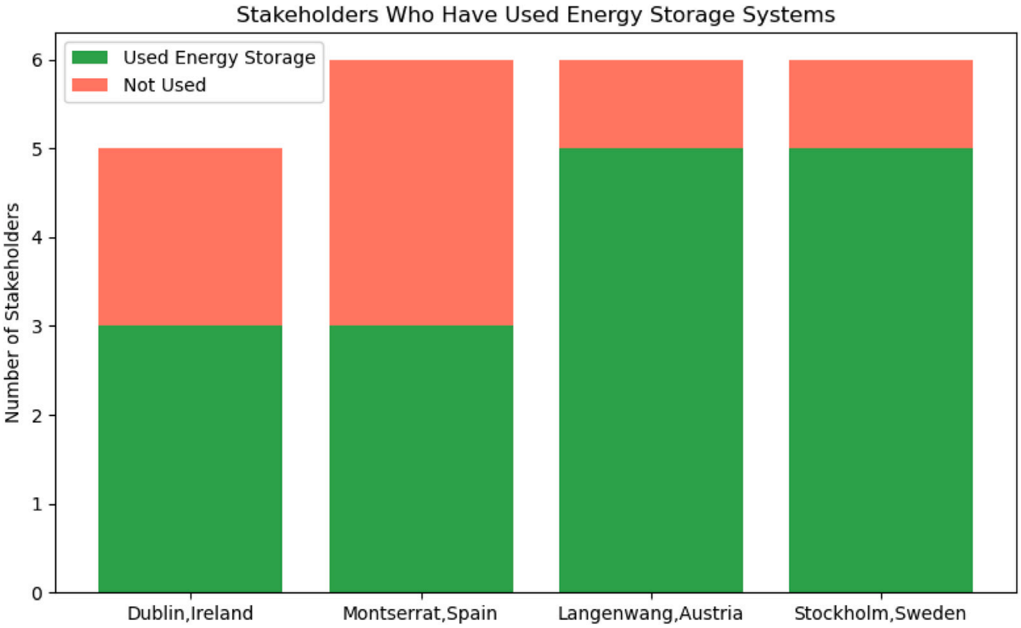


Fig. 8. Stakeholders response on the use of energy storage systems.

and consumers. Management challenges highlighted by stakeholders include running costs, maintenance, consumer knowledge, and concerns from adjoining owners.

Stakeholders welcomed innovative options such as batteries, PCM storage and other TES concepts, yet they also expressed clear reservations. Fig. 9 captures the practical concerns they anticipate developers must still resolve, ranging from heat-loss control and complex system integration to space constraints, running cost and the day-to-day maintenance burden of unfamiliar equipment. Several interviewees who had installed lithium-ion batteries reported that usable capacity fell “a lot” within seven to eight years, prompting early replacement and a switch to virtual storage services. Others questioned the recyclability of battery chemistries and the environmental footprint of the materials involved. Considering TES, respondents highlighted difficulties in keeping storage heaters within comfort ranges, a lack of mature commercial PCM products and the need for installer training before widespread rollout. Maintenance emerged as a recurring concern, with one participant observing that solar-thermal panels often “stop working” in residential settings where servicing is perceived solely as an expense rather than a necessary component of system longevity. Together, these viewpoints underline a cautious attitude towards newer solutions and point to longevity, maintenance simplicity and clear business models as pivotal adoption drivers.

While the interview framework was deliberately broad to capture context-specific insights across four countries, the analysis focused on critical stakeholder perceptions, which were systematically categorised into technical, installation, and management barriers. Within this structure, trust in technology emerged as a key concern, linked to perceived issues with technical maturity and reliability. Financing challenges were evident through stakeholder uncertainty about business models, maintenance costs, and economic efficiency. Regulatory constraints – including legal requirements and coordination with property owners – were also highlighted. Although these barriers are not discrete, they form a cascading system in which low trust undermines investment confidence, which is further impeded by regulatory ambiguity. This systems-based understanding provides a focused interpretation of stakeholder concerns central to TES deployment.

3.5.4. *What technical solutions should be adopted to improve the performance of these systems?*

The stakeholders identified a range of solutions to enhance the performance and adoption of TES systems. A key priority was reducing heat loss and minimising insulation requirements to improve efficiency. Educating consumers about the benefits of charging storage systems using RES was also emphasised, alongside leveraging off-peak or dynamic electricity pricing to optimise charging times. Stakeholders highlighted the importance of developing house-specific controls to tailor TES solutions to individual needs, as well as using multiple storage facilities rather than relying on a single system. Expanding the grid to accommodate TES technologies and integrating TES with existing heating and cooling systems were identified as essential steps. Addressing compatibility issues between TES and other systems was also noted as a critical area for improvement.

To encourage broader adoption, stakeholders suggested reducing capital and operational costs, increasing flexibility in loading and unloading times, and simplifying user interfaces. Improving storage density and efficiency, ensuring adequate time allocation to TES projects, and enhancing accessibility were seen as crucial for optimising TES solutions. Simplifying the implementation process and allocating space for technical installations during the planning stages were also identified as important steps to facilitate deployment. Incentives for property owners were proposed as a means of encouraging adoption, along with the development of advanced control strategies and improved coupling of TES with other components. Proactive engagement from stakeholders, the creation of viable business models, and accelerating the development and integration process were all highlighted as critical for ensuring the success of TES solutions.

3.5.5. *Are thermal energy storage systems suitable solutions to improve energy management by reducing consumption and costs?*

Of the 23 stakeholders interviewed, 16 expressed support for TES systems as effective tools for improving energy management by reducing both energy consumption and costs. However, the question elicited mixed responses, with both supportive and critical viewpoints on the viability of TES solutions. Proponents of TES highlighted several reasons for its potential to enhance energy management. They noted that TES systems are often paired with sources of low-carbon electricity, making them an environmentally friendly addition to existing energy

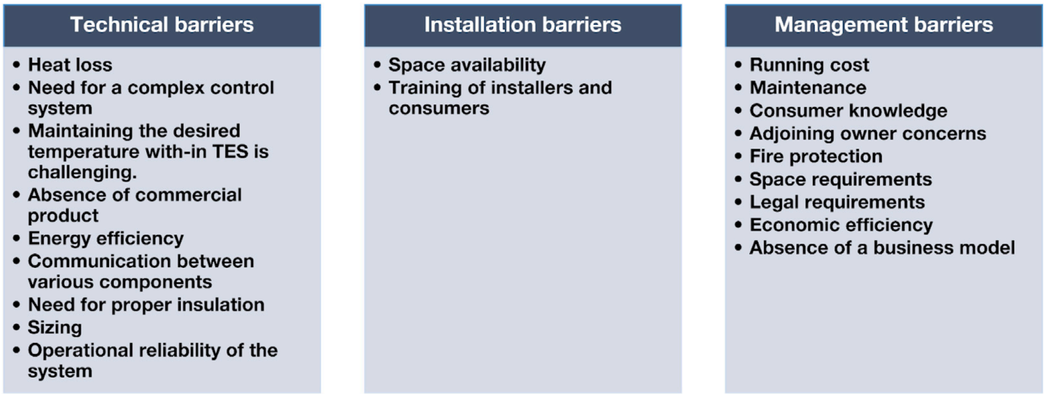


Fig. 9. Identified technical, installation, and management problems associated with energy storage.

systems. TES improves energy management by decoupling supply and demand, enabling better load balancing. Stakeholders also emphasised the cost benefits of using dynamic electricity pricing to charge TES systems and shifting energy loads to off-peak times, both of which can significantly lower operational costs. However, detractors raised concerns about certain limitations of TES systems. One issue was that TES might increase overall energy consumption due to thermal losses associated with storage, potentially offsetting its benefits. Additionally, the lack of commercial availability and proven advantages of advanced technologies, such as PCMs, left some stakeholders sceptical about their practicality. Specific opinions provided further nuance to these perspectives. One respondent stated that *"New TES, such as PCM and sorption storage technologies, are not competitive to actual solutions in terms of investment, installation, and operation costs. The lack of knowledge in most of the facility managers and technicians are also to be considered"*. They also pointed out a lack of knowledge among facility managers and technicians regarding these emerging technologies, which serves as a barrier to broader adoption. Another stakeholder argued that mature and proven solutions such as water tanks should be prioritised before exploring newer technologies. They emphasised the need for better communication of the benefits of alternative TES solutions, many of which remain confined to research settings. Additionally, they highlighted the importance of training installers and technicians on new thermal storage systems to ensure proper maintenance and operation.

3.5.6. *What should be done to make them more accessible, both technically and economically?*

The responses to this question offered a range of perspectives on how to render TES systems both technically and economically accessible. From a technical perspective, stakeholders proposed several measures to improve the operational effectiveness of TES systems. These included the development of monitoring systems and demonstration sites, supported by publicity and training programmes. Stakeholders emphasised the need for simple and understandable solutions, user-friendly interfaces, and extensive, detailed planning for system implementation. Demonstrating the advantages of TES over traditional sensible heat storage solutions was considered crucial for building confidence in these technologies. Further suggestions included the integration of advanced communication technologies to coordinate the optimal performance of existing storage systems. Stakeholders also stressed the importance of investing in research and development to enhance efficiency, securing stakeholder engagement and consensus, and fostering industrial partnerships to promote innovation.

Economically, stakeholders highlighted the importance of making TES technologies commercially available and affordable. They suggested integrating TES systems with dynamic energy pricing models and increasing research and development investments to reduce production and operational costs. Adjustments to regulations and funding guidelines were identified as necessary to facilitate adoption, alongside the introduction of policies offering incentives. Simplifying the installation process to reduce bureaucratic hurdles and introducing government grants and subsidies to lower financial barriers were also recommended. Bringing existing TES technologies to market and clearly quantifying the economic savings they offer consumers were seen as critical strategies for enhancing accessibility.

Furthermore, a stakeholder emphasised the importance of upskilling professionals: *"We need to provide technical support, training, and capacity building for installers, maintenance technicians, and engineers... and establish affordable financing options, such as low-interest loans or on-bill financing"*. From an economic standpoint, the same respondent advocated for increased research and development investment to improve the efficiency and affordability of TES technologies, as well as the establishment of affordable financing options, such as low-interest loans or on-bill financing, to enable consumers and businesses to adopt these systems without requiring significant upfront payments. While fewer opinions were contributed by Spanish stakeholders to this discussion, the responses overall underscore the dual importance of addressing both technical and economic barriers to promote the adoption and effectiveness of TES technologies. By focusing on training, research and development, streamlined processes, and supportive policies, TES systems can be made more accessible, fostering broader adoption and effective integration.

3.6. *Demand response solutions*

The responses to the concept of DSM varied significantly across the use cases. 16 stakeholders demonstrated a clear understanding of the concept of DSM, indicating a relatively high level of familiarity with DR mechanisms among those engaged in the study. In Dublin and Stockholm, stakeholders exhibited high levels of familiarity and support for DSM, with all five respondents in Dublin and five out of six in Stockholm expressing positive views. In contrast, responses in Langenwang and Montserrat were evenly split, with three stakeholders in each location indicating support and three expressing unfamiliarity or skepticism. The concept of DSM appeared relatively novel to stakeholders in the Spanish and Austrian pilots. For example, a stakeholder from Spain noted that, within their context, the supporting technology is not yet available, emphasising the need for parallel efforts to develop technologies that facilitate DSM. In contrast, stakeholders from Stockholm and Dublin demonstrated a much deeper understanding of DSM and a clear recognition of its benefits. In Dublin, there is a notable push to replace existing energy meters with smart meters, which are instrumental in facilitating DSM processes. Stakeholders in this use case expressed interest in participating in such initiatives in the future.

However, very few stakeholders across all use cases reported adopting tools for managing energy storage or peak load shifting. An exception is a stakeholder from Stockholm who is actively conducting

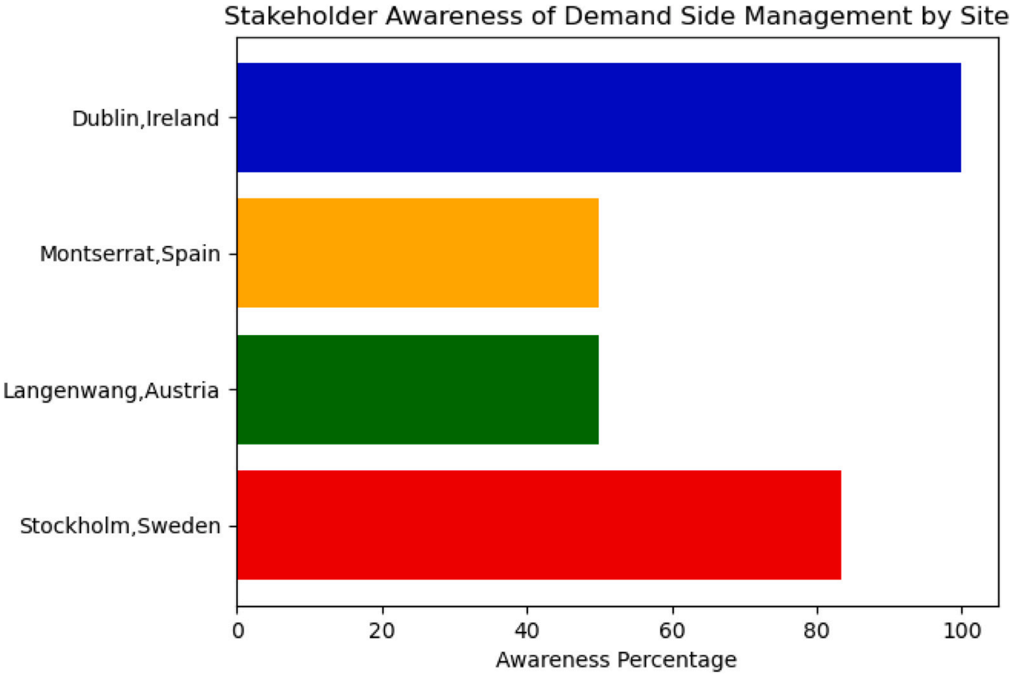


Fig. 10. Awareness of stakeholders on the concept of DSM.

research on this topic. Key insights from stakeholders further emphasise the need for a multi-faceted approach to advance DSM. Respondents highlighted the importance of developing both hardware and software solutions to support DSM initiatives. Specific measures, such as adopting dynamic pricing, implementing smart data monitoring tools, and utilising advanced communication technologies, were deemed essential for effective DSM implementation. Stakeholders also stressed the critical need to address business models, focusing on investment planning and the financial viability of DSM solutions. Furthermore, engaging end users and property owners was identified as a crucial factor, though this remains an ongoing process requiring further development. Fig. 10 depicts comparative awareness of demand-side management across sites.

3.7. Cross-country synthesis

The inclusion of four pilot sites across Spain, Austria, Sweden, and Ireland adds significant analytical value by incorporating diverse climatic, infrastructural, and policy conditions into. Although all sites called for streamlined EU-wide licencing and grid-connection rules, the emphasis placed on specific storage applications differed remarkably. In the Spanish (Mediterranean) pilot, stakeholders – especially site managers and technical directors – emphasised peak-shaving and self-consumption to capitalise on abundant summer PV output. By contrast, Austrian participants in the continental climate highlighted the need for modular seasonal storage, reflecting shoulder-season volatility in demand. In Ireland's Atlantic setting, city-council and academic interviewees struck a balance between these concerns, pointing to the potential of district-level flexibility aggregations without committing to a single use-case. Northern (Swedish) respondents focused on cold-start resilience and seamless integration with district heating, a priority rarely voiced elsewhere. Equity concerns around time-of-use tariffs were mentioned most strongly in Ireland and Sweden – where longer heating seasons exacerbate baseline costs – whereas Spanish and Austrian interviewees viewed price signals as sufficient once technical barriers were addressed. Finally, only the Swedish pilot reported an operational aggregated-storage licence under Article 32 of Directive 2019/944 [52], highlighting how national regulatory maturity shapes stakeholder expectations and readiness. A comparative summary table (Table A.5) synthesises stakeholder perspectives from the four pilot sites – Dublin, Montserrat, Langenwang, and Stockholm – highlighting common themes across varied policy, infrastructure, and cultural contexts. Despite local differences, recurring concerns included high upfront costs, limited public awareness, technical complexity, and maintenance challenges. Stakeholders highlighted the requirement for long-term financial incentives and recommended co-design with end users as a condition for project eligibility. The responses collected across pilot sites reveal a consistent pattern of opportunities and barriers, which form the basis for the interpretative discussion that follows.

4. Discussion

This section synthesises the stakeholder feedback to identify cross-cutting themes and propose strategic recommendations for enhancing the implementation of TES and DSM.

4.1. Summary of responses

The stakeholders demonstrated a clear understanding of energy transition and the necessity of moving away from fossil fuel-based energy generation. They emphasised the critical role of renewable energy, highlighting its sustainability and eco-friendliness as key attributes for achieving energy transition. However, they also acknowledged significant challenges, including the lack of tools, insufficient political and economic policies, and limited information. While renewable energy is strongly supported, stakeholders expressed concerns about supply security, emphasising the need for complementary systems. Public engagement at all levels was identified as crucial for a successful energy transition, along with overcoming challenges related to energy storage, infrastructure, economics, and knowledge gaps.

Energy efficiency was regarded as a critical component of energy transition, valued for its ability to reduce consumption and waste. Stakeholders believed that raising awareness, providing user training, and fostering a change in user mentality are essential steps to achieving energy efficiency. They noted that its implementation has resulted in significant reductions in energy consumption and cost savings, reflecting widespread support for energy efficiency initiatives. Among energy technologies, solar PVs emerged as the preferred solution due to its affordability, accessibility, and cost-effectiveness. This preference was evidenced by a rise in PV installations, underscoring stakeholders' consensus on its practicality. In terms of energy storage, stakeholders predominantly utilised hot water tanks and battery systems, though concerns about battery longevity and performance were raised.

Barriers to adopting energy storage technologies included cost, space constraints, lack of information, limited lifespan, and environmental concerns regarding toxic materials. Awareness of advanced TES solutions, such as PCM and TCM, was largely confined to academic researchers, highlighting the requirement to make these technologies more accessible and comprehensible to a broader audience. PCM and TCM solutions were considered as less competitive than existing options in terms of investment, installation, and operational costs. Stakeholders highlighted the need to improve market accessibility for these technologies while addressing economic barriers. Finally, the concept of DSM was familiar to stakeholders, and they recognised its potential in shifting energy consumption to off-peak hours through dynamic pricing. However, they were sceptical about its ability to reduce overall energy consumption, viewing it more as a tool for reshaping usage patterns rather than decreasing total demand. A lack of tools and resources to facilitate effective DSM was also identified as a challenge, further highlighting the requirement for practical solutions and resources to maximise its potential.

This study reveals that stakeholders identified institutional fragmentation, financial uncertainty, limited public awareness, and the need for inclusive engagement as primary challenges to TES deployment. Notable variation was observed across national contexts: Austrian and Swedish participants emphasised regulatory clarity and technical feasibility, while Irish and Spanish stakeholders focused more acutely on economic constraints and the importance of social acceptance. These findings resonate with patterns identified in the existing literature. Concerns regarding fragmented regulatory environments and institutional lock-in are similarly discussed in [24,32]. The importance of participatory processes and community engagement is also reflected in [6,37]. This work offers a distinctive contribution through its direct integration of stakeholder insights into participatory project design, including co-creation activities such as World Café workshops. Moreover, its cross-national, site-based qualitative design sets it apart from studies with a more aggregated or policy-focused lens, such as [33,36]. In this way, the study advances the literature by providing empirically grounded, context-sensitive insights into the socio-institutional dynamics of TES implementation.

4.2. Recommendations for enhancing the adoption and implementation of energy storage solutions

To facilitate the successful adoption and implementation of advanced TES technologies, several interrelated technical, economic, and sociopolitical dimensions must be addressed. Considering the issue of cost-effectiveness, the proposed storage solutions must demonstrate financial viability by offering cost parity – or a clear advantage – relative to the replacement or upgrading of incumbent systems. This imperative underscores the need to develop robust and sustainable business models that can incentivise stakeholder investment, particularly under conditions of uncertain return on investment. Moreover, the comparative advantage of emerging TES technologies – such as those employing PCM and TCM – must be clearly articulated in relation to existing sensible storage systems, which are currently favoured for their affordability, accessibility, and operational simplicity. Without a compelling value proposition that differentiates these advanced solutions, uptake is likely to remain constrained. Consequently, strategic communication of these benefits is essential to overcoming prevalent scepticism and accelerating broader acceptance.

In parallel, operational requirements must be explicitly addressed. Stakeholders consistently emphasised the importance of optimised control strategies capable of effectively coordinating the multiple components of TES systems. Such strategies must support dynamic load-shifting, interface usability, and thermal comfort, particularly in residential and community-scale applications. Furthermore, design considerations must account for practical constraints, including physical space limitations, ease of maintenance, and user interface simplicity. These user-centred concerns highlight the need for modular, low-intervention designs that reduce maintenance challenges while enhancing system transparency and accessibility. Dissemination of knowledge beyond the academic and technical communities remains a critical challenge. Awareness of TES technologies – particularly PCM and TCM-based systems – remains largely confined to expert stakeholders. To bridge this gap, targeted outreach and capacity-building initiatives must be implemented. Training programmes for installers, technicians, and energy service providers are necessary to ensure proper deployment and maintenance. Simultaneously, broader public education efforts should aim to challenge prevailing assumptions that batteries are the default solution for solar PV integration, driven by their technological maturity and familiarity. Positioning TES as a viable alternative requires a recalibration of public perception and technical discourse alike.

The integration of DSM technologies is likewise essential to maximising the benefits of TES. In cases where DSM infrastructure is underdeveloped or unavailable, the role of TES may need to shift from peak shaving to enhancing the reliability of renewable generation. This interdependence requires parallel investments in DSM capability development, thereby enabling TES systems to respond effectively to dynamic pricing signals and other grid flexibility requirements. Demonstration-based validation remains pivotal to fostering trust and catalysing market acceptance. Stakeholders expressed a clear need for transparent, accessible performance data from pilot sites. Such empirical evidence is vital not only to support claims of system efficacy but also to inform consumer choice and regulatory policy. Accordingly, the dissemination of detailed and verifiable test results should be integral to all TES deployment strategies.

The developed stakeholder engagement process significantly informed both the technical and operational dimensions of TES system development. A series of figures presented in the manuscript illustrate the iterative nature of this process. Fig. 11 outlines the high-level control framework, wherein real-time inputs – such as PV generation forecasts, dynamic electricity tariffs, and carbon cost considerations – are processed via Python-based optimisation algorithms to generate adaptive load-shifting strategies. This aligns with stakeholder preferences for cost-effective, user-friendly, and environmentally conscious solutions. Finally, Fig. 12 maps the stakeholder engagement model, demonstrating how semi-structured interviews shaped technical specifications. Stakeholder-identified concerns – including spatial constraints, cost sensitivity, and maintenance requirements – were incorporated into component sizing, interface design, and transparency measures. Fig. 13 depicts the integrated TES-DSM architecture, detailing the coordinated operation of PV arrays, TES units, heat pumps, and aggregators under a centralised control system. This schematic exemplifies stakeholder-driven system integration tailored to context-specific user needs and infrastructure conditions.

The participatory methodology further incorporated structured co-creation, co-design, and co-assessment activities. To demonstrate how stakeholder feedback informed system design and operation, a structured engagement model was adopted (Fig. 14), incorporating co-creation, co-design, and co-assessment activities throughout the project lifecycle. During the co-creation phase, early engagement identified affordability, usability, and spatial compatibility as key priorities, leading to the development of modular TES systems with simplified user interfaces. In the co-design phase, stakeholder input – particularly from urban contexts such as Montserrat (Spain) – guided spatial optimisation and integration strategies. Finally, in the co-assessment phase, interest

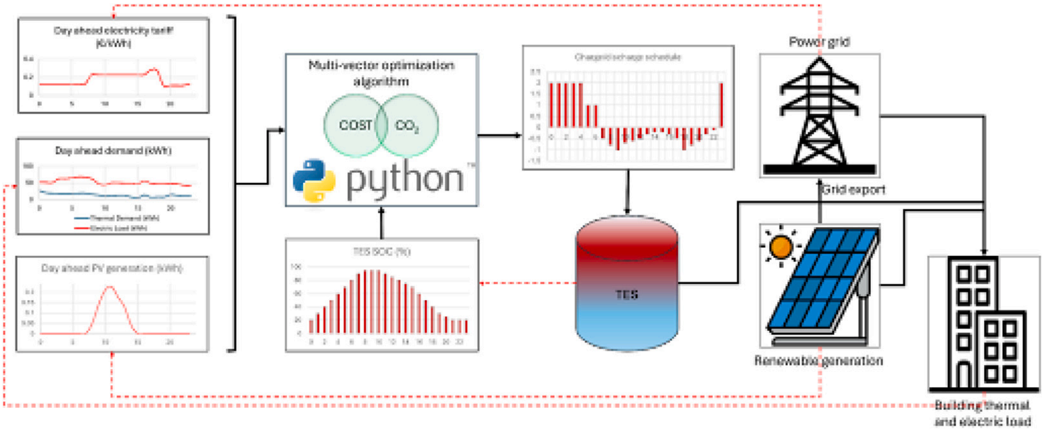


Fig. 11. TES charge/discharge control based on DSM.

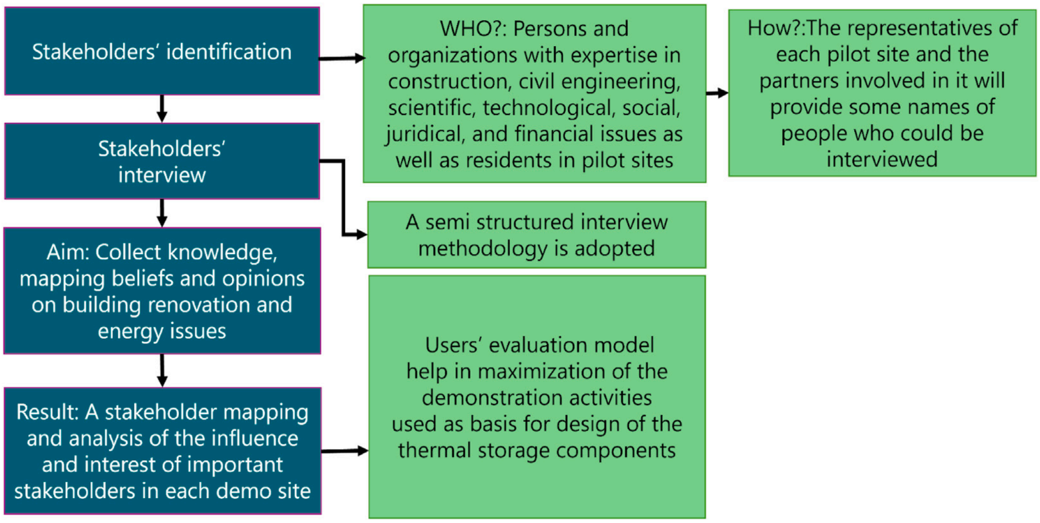


Fig. 12. Overview of stakeholder interview method.

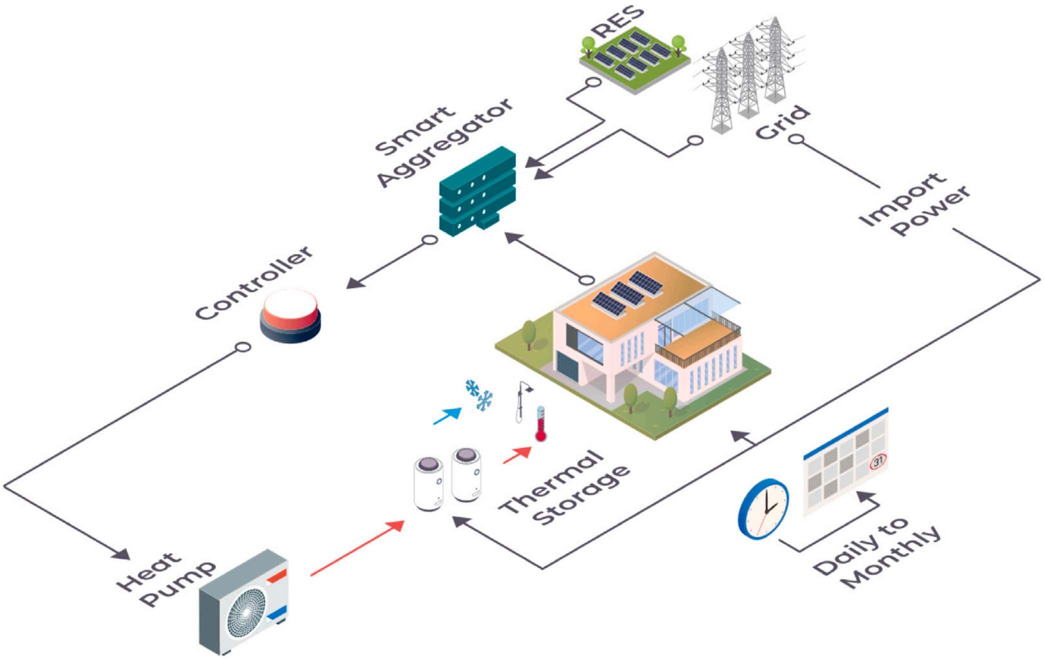


Fig. 13. TES-DSM integration model.

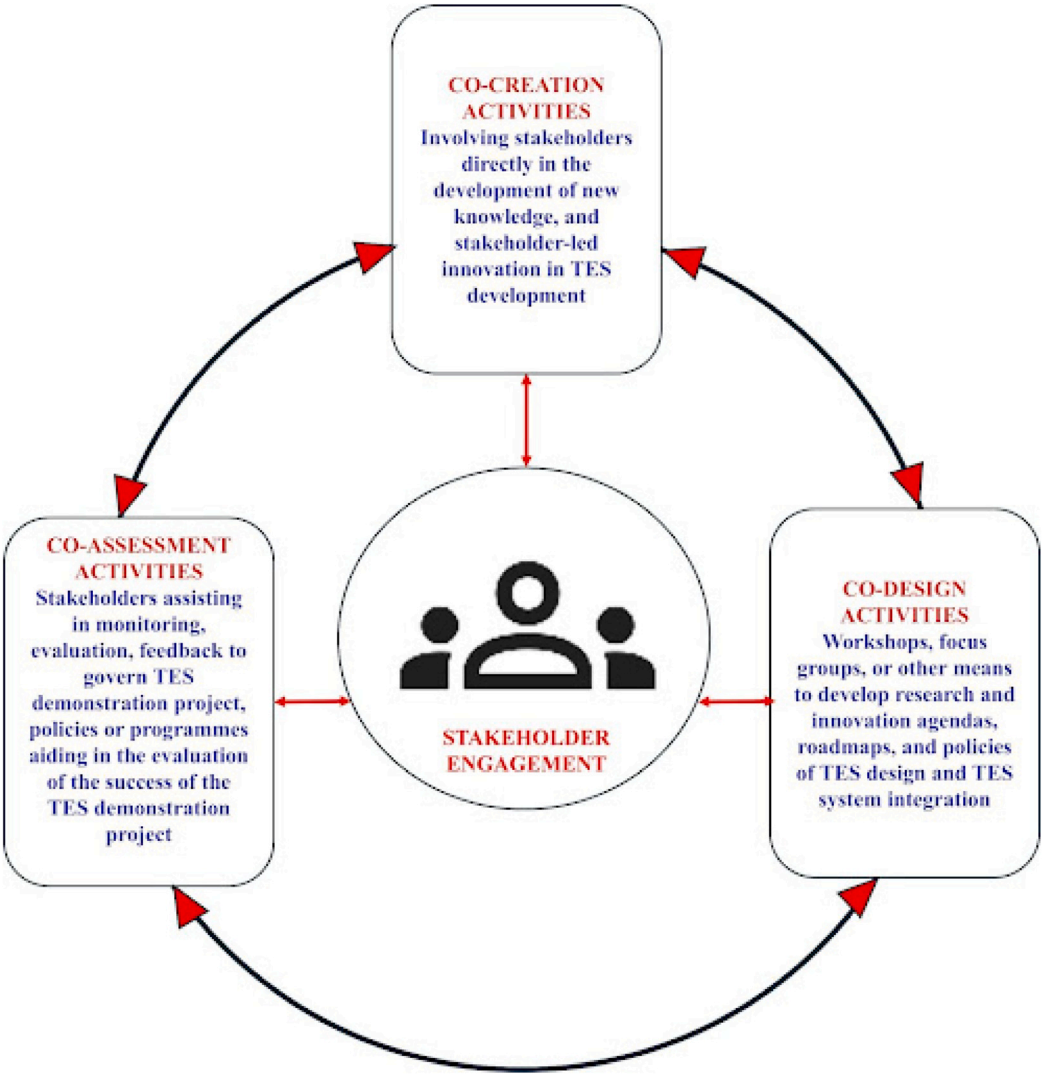


Fig. 14. Stakeholder engagement in TES integration to maximise the impact of the HYSTORE project.

Table A.1
Summary of the reviewed literature.

Reference	Technological focus	Barriers addressed	Implementation scale	Research scope	Methodology	Key findings
[48]	Solar PV	Technical, economic	Local	Context-specific barriers	20 stakeholder interviews, stakeholder interaction framework (qualitative)	Policy fragmentation, resident distrust, weak community engagement, atomisation of urban society
[46]	Renewables (solar, wind)	Financial, political	Regional	Financial innovation analysis	Comparative policy analysis (qualitative)	Authority and temporality matter; national context determines stakeholder influence
[47]	Solar PV	Governance, political	National	Comparative governance	Process tracing, document analysis (qualitative)	Institutional legacies and coordination drive solar success
[49]	Solar PV	Technical, economic	Local	Urban-specific barriers	Innovation-system functions and interviews (qualitative)	Lack of institutional support, financing barriers, geopolitical influence
[39]	Demand response	Economic, regulatory	Regional	Innovative business models	Stakeholder interviews, value-proposition design (qualitative)	Diverse stakeholder needs, importance of user engagement, business-model complexity
[19]	Demand response	Technical, market	National	Aggregator roles	Case study, semi-structured interviews with industrial stakeholders (qualitative)	Regulatory uncertainty, need for trust and data transparency, aggregator-user alignment critical
[6]	Demand-side management	Stakeholder alignment, regulatory	Local	Inclusive governance	Case studies, stakeholder mapping, governance analysis (qualitative)	Distributed governance supports participation, but requires coordination and institutional capacity
[38]	Thermal energy storage	Economic, market	National	Detailed business models	Business-modelling interviews, value mapping (qualitative)	TES offers value across system services, but requires regulatory and financial alignment
[8]	Thermal energy storage	Regulatory, market, stakeholder	Local	Stakeholder-driven analysis	Stakeholder interviews, barrier typology (qualitative)	Economic, awareness and institutional barriers dominate, with fragmented incentives
[37]	Positive-energy districts	Regulatory, technical	Regional	Practical implementation insights	Case studies of multiple EU PEDs (qualitative)	Misalignment of visions, governance fragmentation, inertia in institutional change
[36]	Renewables	Investment, policy	National	Risk-focused policy	Policy and stakeholder analysis (qualitative)	Grid instability, land acquisition, regulatory gaps
[35]	Electricity policy	Political, governance	Regional	Comparative regional analysis	Comparative political-economy analysis (qualitative)	Stakeholder alliances shape coupling success; institutional misfits hamper progress
[34]	Renewable energy	Network, economic	Regional	Innovation ecosystems	Case study, innovation-network mapping (qualitative)	Intermediaries crucial in shaping RE innovation paths
[33]	Microgrids	Regulatory, economic	Local	Complexity navigation in microgrids	Qualitative multi-level stakeholder analysis	Coordination complexity, emerging governance gaps

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Table A.1 (*continued*).

Reference	Technological focus	Barriers addressed	Implementation scale	Research scope	Methodology	Key findings
[32]	Renewables (solar, wind)	Market distortions, political	National	Sectoral policy reforms	Comparative historical analysis, synthetic control (qualitative)	Legacy infrastructures constrain new RE policies
[31]	Geothermal energy	Financial, regulatory, social	Regional	Comparative geothermal opportunities	Cross-case comparative study, semi-structured interviews (qualitative)	Social acceptance, permitting and coordination challenges vary by case
[30]	Renewables + hydrogen storage	Financial, technical	Local	Hydrogen-storage analysis	Simulation modelling and stakeholder-impact analysis (quantitative)	Storage increases flexibility and profitability; stakeholder roles are interdependent
[29]	Energy efficiency (ICT)	Technical, data management	Regional	ICT for energy efficiency	ICT analysis (qualitative)	Digitalisation can enhance transparency and reduce verification cost
[27]	Energy efficiency	Financial, market	National	Retrofitting financial mechanisms	Policy-document analysis (qualitative)	Narrow cost-centric framing impedes transformative EE policy
[26]	Climate policy	Governance, political	Local	Discourse-impact analysis	Discourse analysis (qualitative)	Municipalities replicate national limits rather than challenging them
[25]	Electricity-market coupling	Political, institutional	Regional	Comparative market integration	Case studies, stakeholder mapping, governance analysis (qualitative)	Distributed governance supports participation, but needs institutional coordination and capacity-building
[24]	Battery recycling/second-life	Regulatory, market, safety	National	Second-life-market barriers	13 expert interviews, PESSTEL analysis, stakeholder workshop (qualitative)	Institutional fragmentation, repurposing challenges, safety-and-certification hurdles, economic-viability concerns

in DSM prompted the design of time-based charging schemes, while concerns regarding system maintenance led to the establishment of dedicated training programmes for relevant personnel. In addition to technical implications, stakeholder feedback yielded several actionable policy recommendations. Across all four pilot sites, interviewees consistently advocated for stable, long-term financial incentives – including investment grants, low-interest loans, and on-bill financing mechanisms – to reduce capital cost burdens. Regulatory frameworks should incorporate TES and DSM into national building codes, district heating guidelines, and grid-connection protocols, while preserving implementation flexibility for local authorities. Moreover, stakeholders recommended that formalised co-design processes be instituted as eligibility criteria for public funding schemes. While these insights emerged from diverse European contexts, the underlying issues – namely, regulatory fragmentation, cost uncertainty, and awareness deficits – are globally relevant.

Beyond informing deployment strategies, the stakeholder interviews surfaced design-relevant insights with direct implications for TES development. Concerns regarding spatial limitations, maintenance burdens, and system complexity reveal a need to reframe user expectations as integral to the design process. Rather than treating end-user considerations as post-design constraints, the study positions them as foundational inputs into the engineering cycle. Simplified control interfaces, transparent labelling, and modular architectures can address user apprehensions, improve system operability, and enhance long-term satisfaction. In this way, stakeholder engagement functions not merely as a communicative exercise but as a diagnostic tool for identifying latent design tensions and enabling iterative refinement. Finally, while the study findings are based on four European countries, the systemic challenges addressed – such as fragmented stakeholder coordination and regulatory uncertainty – are observed globally [36,47]. The stakeholder-driven methodology utilised in the current paper aligns with those in [6,34], indicating its broader adaptability. Replicating this framework in other regional contexts would not only validate the results but also expand global insights into context-sensitive, scalable energy flexibility solutions.

4.3. Policy implications

Stakeholder interviews across the four pilot sites revealed several interrelated policy and regulatory challenges associated with the integration of energy storage and DSM technologies. A consistent theme was that regulatory frameworks have not kept pace with technological developments — particularly in the case of behind-the-meter batteries and TES systems. Licencing procedures, grid-connection rules, and building standards remain fragmented or outdated, undermining implementation efforts. Harmonising permitting protocols, removing size-based licencing thresholds, and enabling aggregated storage to participate in balancing markets under unified licencing schemes were identified as priority reforms. These changes would operationalise Article 32 of the recast EU Electricity Directive [52], though stakeholders emphasised that local distribution system operators must be provided with explicit cost-recovery mechanisms before such reforms can be implemented.

In addition to regulatory alignment, stable and long-term financial incentives were widely viewed as essential to reducing capital cost burdens. Interviewees advocated for instruments such as investment

Table A.2
Interview questionnaire.

Question number	Question title	Follow up questions
Q1	Please introduce yourself and tell me about you.	Collect demographic details of the interviewee, including gender, age, occupation, education, etc.
		Gather information on the interviewee's interaction with the demonstration site, such as their role and the nature of their involvement.
Q2	What do you know about the energy transition?	–
Q3	How can we help energy transition?	–
Q4	How do you evaluate the role of renewable energy in achieving the energy transition?	–
Q5	How can we boost renewable energy production and reduce reliance on polluting sources?	–
Q6	What is your idea of energy efficiency?	Where and from whom did you learn about energy efficiency?
		What made you think about energy efficiency and its benefits? OR
		Why do you not know anything about energy efficiency?
		What would it take to make people aware of energy efficiency solutions or tools?
Q7	What are the most appropriate tools for energy efficiency improvement?	Is your knowledge of energy-efficient technologies from personal interest or from friends/ acquaintances in the energy sector?
		Do you think that individual behaviour is also important for more efficient energy management?
Q8	Have you ever used appliances or other means to make your home, office or business more energy efficient?	Who and what made you choose this product or solution?
		How much did the possibility of government incentives influence your choice?
		Was your choice driven by economic factors, environmental concerns, or both?
Q9	How do you rate the effectiveness of energy efficiency solutions in saving energy and reducing costs?	Has the increase in energy efficiency led to an increase in energy consumption (rebound effect), rather than a decrease?
Q10	Which sustainable energy technologies are the most technically accessible and affordable?	–
Q11	Do you have on-site renewable energy systems or other decarbonisation technologies like PV, geothermal, or CHP?	–
Q12	What emerging technologies or systems might interest you for your home, business, office, neighbourhood, and why?	–
Q13	Have you ever used energy storage systems?	If not, what were the reasons for not using them?
		If yes, which storage systems have you used?

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Table A.2 (*continued*).

Question number	Question title	Follow up questions
Q14	Have you heard of or are you familiar with thermal energy storage systems?	If not, would you like to know more about it?
		What kind of information would you like to receive?
		If yes, why have you never used one?
		Had you already thought of using it and why?
Q15	What were or are the technical or installation or management problems to be addressed?	–
Q16	What technical solutions should be adopted to improve the performance of these systems?	–
Q17	Are thermal energy storage systems suitable solutions to improve energy management by reducing consumption and costs?	–
Q18	What should be done to make them more accessible, both technically and economically?	–
Q19	Have you heard about demand response?	If not, would you like to know more about it?
		What kind of information would you like to receive?
		If yes, are you participating in any demand-side management or energy flexibility programs?
		Are you interested in being part of one in the future?
		Are you adopting tools to manage energy storage and peak load shifting?
Q20	Finally, any more questions?	Is there anything you would like to add?
		Is there something else you think we should know about?

grants, low-interest loans, and on-bill financing mechanisms. Moreover, tariff design was seen as critical for shaping user behaviour and social outcomes. Time-of-use pricing and capacity-based network charges were regarded as indispensable tools for enabling flexibility, yet interviewees warned that price signals alone may reinforce existing inequities. A hybrid incentive model was therefore proposed: a universal baseline credit financed through network charges could ensure inclusivity, while a performance-based supplement tied to verifiable demand response would reward active participation. This approach adheres to the polluter-pays principle while mitigating the regressive effects of purely market-driven schemes.

To address procedural fairness and ensure broad legitimacy, stakeholders highlighted the need for formalised co-design processes. Such processes should be embedded not only in project planning but also as eligibility criteria for accessing public funding. The developed member-checking protocol – where participants reviewed and validated their interview transcripts – was cited as a transferable model for community-level impact reporting. Trust-building and transparent benefit-sharing arrangements were seen as essential preconditions for stakeholder engagement, particularly in early-stage deployments. Turning these recommendations into action requires a sequenced and adaptive policy approach. In the short term, distribution system operators could publish standardised protocols for battery aggregation and develop model contracts for community storage. In the medium term, national regulators might initiate dual-incentive tariff pilots across diverse regions and commission independent assessments of their social impact. Over the longer horizon, distributed storage resources could be integrated into capacity-remuneration mechanisms, provided they meet defined environmental and equity benchmarks. Such a phased strategy allows for investment certainty while leaving space for iterative refinement based on stakeholder feedback.

4.4. Limitations and future research directions

This study presents context-specific findings derived from 23 qualitative interviews conducted across four European demonstration sites – Spain, Austria, Sweden, and Ireland – as part of the HYSTORE project. Participants were strategically selected through purposive sampling to ensure diversity in professional roles, technical expertise, and geographic distribution. The sample included policymakers, engineers, facility managers, community representatives, energy users, and local authorities directly involved in the demonstration projects. This approach was intended to yield in-depth, context-rich insights rather than statistically representative data. Moreover, the study underrepresents certain stakeholder categories, including disengaged citizens, national-level regulators, and large-scale energy providers. While every attempt was made to reduce selection bias and increase representativeness, the qualitative nature of the study means that the findings are presented as illustrative and context-specific, rather than statistically generalisable. This limitation partly reflects constraints in research resources and project timelines; consequently, the number of respondents was restricted. Future research should therefore aim to enhance statistical saturation and robustness by expanding the sample size, particularly through increasing the number of representative user and enterprise interviews in each country. Moreover, despite efforts to include diverse stakeholders, certain groups – such as ordinary residents and low-income households – remain insufficiently represented, underscoring the need for more inclusive sampling strategies in subsequent studies.

The methodological design followed a qualitative, exploratory approach, employing open-ended, semi-structured interviews to investigate stakeholder perceptions, expectations, and concerns. Data analysis was conducted thematically and interpretively, without the use of

Table A.3
Stakeholder types covered from the four demonstration sites.

Demographic information	Ireland	Spain	Austria	Sweden
Stakeholder 1 – Role	Team lead in city council	Technical director	Municipal	Academic Department Head
Type	External	Internal	External	Internal
Age	63	53	45	–
Education	University	University	Secondary general	University
Interaction	Work	Work	Work	Work
Stakeholder 2 – Role	Academic	Architect	Managing director	Academy
Type	Internal	External	Internal	Internal
Age	> 50	53	48	–
Education	University	University	University	University
Interaction	Work	Work	Work	Work
Stakeholder 3 – Role	Academic	Tourism facility manager	Managing director	Postdoc researcher
Type	External	External	Internal	Internal
Age	44	60	34	–
Education	University	University	Secondary vocational	University
Interaction	Work	Work	Work	Work
Stakeholder 4 – Role	Academic	Project manager	Managing director	Academic researcher
Type	Internal	Internal	Internal	Internal
Age	> 50	44	43	–
Education	University	University	University	University
Interaction	Work	Work	Work	Work
Stakeholder 5 – Role	Academic	IT developer	Technical employee	Director of lab
Type	Internal	External	Internal	Internal
Age	43	29	51	–
Education	University	University	University	University
Interaction	Work	Work	Work	Work
Stakeholder 6 – Role	–	Managing director	Administration	Academic researcher
Type	–	External	External	Internal
Age	–	36	33	–
Education	–	University	Secondary vocational	University
Interaction	–	Work	Work	Work

statistical modelling, automated sentiment analysis, or inferential techniques. This approach prioritised understanding the “why” and “how” behind stakeholder perspectives over quantifying responses or identifying statistically significant patterns. Consequently, while key barriers to TES adoption – such as high capital costs, technical complexity, low user awareness, and maintenance challenges – were consistently identified across the sites, these were not statistically prioritised or weighted in this phase. Additional limitations stem from the variability in data collection methods. Interviews were conducted both in-person and online and, in several cases, required translation into English. These mixed formats may have introduced minor inconsistencies in communication, potentially affecting how participants articulated their views or how their responses were interpreted.

Furthermore, the study does not explicitly apply established adoption models such as the technology acceptance model [53] or the unified theory of acceptance and use of technology (UTAUT) [54] in its current qualitative phase. Nevertheless, the insights gathered informed the broader user engagement strategy of the HYSTORE project and laid the foundation for subsequent research activities. To address these limitations and build on the findings, future research will include a large-scale structured survey targeting 250–300 participants. This next phase, grounded explicitly in the UTAUT framework, will engage a wider range of stakeholders, including disengaged community members, national authorities, and industry representatives. The structured format will enable the quantitative assessment of core adoption factors – such as performance expectancy, effort expectancy, social influence, and facilitating conditions – and will allow for the statistical prioritisation of perceived barriers to TES adoption. Lastly, while the study acknowledges that stakeholder perspectives are shaped by differing national policy frameworks, infrastructure maturity, and cultural norms, its principal objective was to identify shared challenges and insights across sites. Despite contextual variation, several common themes emerged, suggesting that certain barriers to TES adoption may be broadly relevant. However, the potential influence of contextual bias in cross-site comparisons is recognised and should be considered when interpreting the results. Building on these observations, future studies could also employ longitudinal or phased interview designs to capture the dynamic evolution of user perceptions, technological performance, and policy responses over time, thereby extending the analytical depth beyond what is possible in a single cross-sectional study.

5. Conclusions

This research highlights the critical role of stakeholder engagement and user-centric approaches in addressing the challenges of the global energy transition. By leveraging qualitative data from diverse stakeholders, including policymakers, academics, industry professionals, and end-users, the study offers a nuanced understanding of the barriers, opportunities, and practical considerations associated with sustainable energy technologies, energy efficiency, and thermal energy storage systems. The primary contribution of this work lies in its integration of stakeholder insights into the development and evaluation of energy transition strategies. By conducting structured interviews across multiple demonstration sites in varied European climates, the study captures a wide range of perspectives, ensuring that proposed solutions are

Table A.4
Stakeholder interview protocol.

Research phase	Methodology employed	Key tools & Instruments	Primary outputs	Recommendations & Best practices for replication
1. Stakeholder Identification & Engagement	Purposive Sampling: Collaborate with local pilot site leaders to identify key stakeholders based on their relevance and expertise.	- Pre-defined stakeholder categories (e.g., academic, technical, municipal, end-user). - Local partner networks and contacts.	Targeted list of 23 diverse stakeholders across 4 countries, representing multiple roles and sectors.	- Classify stakeholders into seven categories (e.g., decision-makers, professionals, residents). - Ensure diversity in gender, role, and context. - Apply purposive and snowball sampling methods. - Ensure diversity across roles (technical, policy, user).
2. Questionnaire Design	Semi-structured Interview Framework: Collaborative design by a multidisciplinary international team; open-ended for enhanced responses.	- 20-question guide organised into 5 thematic sections. - Follow-up prompts and clarification hints.	Validated and context-aware questionnaire suitable for diverse stakeholder groups.	- Translate and culturally adapt the questionnaire. - Allow interviewers flexibility to follow emergent themes.
3. Data Collection	Qualitative In-depth Interviews: Conducted online or in-person depending on logistics and interviewee preference (~40 mins each).	- Audio recording devices - Interviewer notes - Informed consent forms	23 audio-recorded interviews with corresponding detailed interviewer notes.	Ensure privacy and a comfortable setting to promote open discussion.
4. Data Processing & Analysis	Verbatim Transcription & Validation: Audio and notes transcribed and sent back to participants for validation ("member checking").	- Transcription software - Secure shared repository - Thematic coding framework based on research themes	- 23 validated transcripts - Coded dataset organised by themes (Energy Transition, Efficiency, etc.)	Use systematic coding to maintain consistency and analytical rigor.
5. Data Synthesis & Visualisation	Structured Visualisation & Comparative Analysis: Synthesising qualitative findings into visual formats for interpretation.	- Comparative summary tables - Quantitative charts and graphics (bar/pie/icon-based) - Geographic maps, word clouds	- Figures 1–10 presenting key findings - Comparative stakeholder summary table	- Visual formats help make qualitative data accessible. - Use tables for cross-country comparisons and charts to highlight major trends/statistics.

context-sensitive and aligned with real-world needs. This stakeholder-driven methodology provides actionable pathways to address technical, economic, and social barriers to the adoption of TES and demand-side management systems. Key findings underscore the importance of improving awareness, fostering collaboration among stakeholders, and aligning policy frameworks with user needs. The research identifies critical areas for intervention, such as reducing the upfront costs of energy-efficient technologies, streamlining regulatory processes, and enhancing technical and financial support for TES and DSM adoption. Moreover, the study highlights the need for robust communication strategies to convey the economic and environmental benefits of these solutions, thus building confidence and facilitating broader adoption.

By integrating stakeholder perspectives into energy system design and implementation, the research advances a participatory framework that enhances the feasibility, scalability, and sustainability of energy transition initiatives. The findings provide practical guidance for policymakers, industry leaders and researchers by translating stakeholder priorities into concrete regulatory levers, financing instruments and engagement requirements. Because the study covers Mediterranean, oceanic and sub-arctic contexts, these recommendations are adaptable to regions with different climatic and socioeconomic conditions, provided the same cost, technical and governance barriers are present. This study exemplifies the transformative potential of stakeholder-driven research in shaping energy policy and innovation. By bridging the gap between technological potential and societal acceptance, it contributes to a more inclusive and adaptive pathway towards global sustainability goals.

This study provides exploratory insights into stakeholder perspectives on thermal energy storage across four European pilot sites. However, it is important to acknowledge its limitations, including a modest sample size and a focus on individuals already engaged in the demonstration projects. Future research will address these constraints by expanding stakeholder participation to include underrepresented sectors and regions, and by implementing a large-scale, theory-based survey using the UTAUT framework. This next phase will enable quantitative validation of the findings and support more generalisable, policy-relevant conclusions.

CRediT authorship contribution statement

Adamantios Bampoulas: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Anandhi Parthiban:** Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Agatino Nicita:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing. **Eleni Mangina:** Conceptualization, Writing – review & editing, Funding acquisition, Project administration, Supervision. **Mohammad Saffari:** Conceptualization, Writing – review & editing, Funding acquisition, Project administration, Supervision.

Table A.5
Comparative summary of stakeholder views across four case-study countries.

Theme	Dublin, Ireland	Montserrat, Spain	Langenwang, Austria	Stockholm, Sweden
Perception of the energy transition	Understood as a high-level, global shift defined by research and driven by EU/national policies and targets.	Seen as a practical paradigm shift in production and use, with knowledge derived from experiential roles like “user and manager”.	Defined by concrete actions such as exiting fossil fuels, adopting district heating, and promoting local innovation in transport and power.	Viewed as a “top topic” that is urgent and already well under way, with a deep focus on established systems such as district heating and RES.
Views on energy efficiency	Defined by technical metrics and system losses; calls for a shift in mindset from efficiency to sufficiency.	Understood simply as “not wasting”. Strongly motivated by rising energy prices, which drive behavioural change.	Focus on simple measures like switching off lights and sensible heating use. Skepticism about the meaningfulness of formal efficiency classes.	Viewed from a system perspective. Main challenge: the lack of communication and integration between different energy systems in a building.
Technology preferences and accessibility	PVs and HPs are the most recognised and accessible technologies. Awareness of life-cycle carbon benefits is high.	Familiarity with common technologies (LED, PV), but significant concern over the lack of maintenance culture, leading to failures.	Strong familiarity with a range of heating systems (HPs, biomass, pellets), with a clear understanding of the cost differences.	Highly mature market with widespread use of advanced technologies such as ground-source HPs and FTX ventilation systems, often viewed as standard solutions.
Perceptions of TES	Good understanding of hot-water tanks and storage heaters, including the technical challenges of scheduling and control.	Perceived as immature, not commercially available, too costly, and impractical owing to a lack of space, information, and trust.	Known to technical experts but not widely understood or available to the general public.	Actively used and researched (water tanks, PCM). Key barrier: the lack of viable business models to compete with simple water tanks.
Awareness of DR	Understood as a key strategy for load shifting, with interest directly linked to the national smart-meter rollout.	Perceived as a novel concept requiring significant future development.	Stakeholders are generally unfamiliar with the term or its practical application.	The discussion has moved beyond awareness to the practical challenges of implementation — solving the business model and financial viability.
Major identified barriers	Lack of public confidence, difficulty of sustaining long-term behavioural change, need for better top-down policies and communication.	High costs, lack of practical information, the complexity of new systems, a critical absence of tools and a maintenance culture for SMEs.	High cost of technologies, bureaucratic hurdles in project implementation, and social challenges such as “energy poverty”.	Need for clearer business models, better incentives for new tech, and addressing challenges in integrating multiple systems effectively.

Declaration of competing interest

The authors 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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Appendix. Supplementary tables

See Tables A.1–A.5.

Data availability

Data will be made available on request.

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