PED StepWise

Best practices report

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Authors	Georg Wolfmayr, Farzin Golzar, Tamara Lühr, Sara Herreras Martínez
Reviewers	Gerhard Hofer, Christoffer Orinius

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Executive summary

This Best Practices Report of the PED StepWise project, identifies effective strategies and innovative solutions for overcoming key challenges in decarbonizing existing buildings at the district level. The findings aim to inform and support the implementation of Positive Energy Districts (PEDs) and CO2 reduction efforts in the living labs of Vienna, Malmö, and Utrecht.

As a result of two co-design sessions with various research partners across the three living labs, three topics were selected for investigation in the Best Practices review. The topics aligned with existing challenges and interesting options to investigate to help the three living labs achieving their CO2 reduction ambitions. The three topics investigated in the report are: Energy-sharing, how to reduce energy through behavioral changes, and best practices to overcome organizational and governance challenges.

Energy sharing plays a critical role in PEDs and energy communities, enabling local collaboration in energy management. The report highlights three key aspects:

- Policy and regulatory frameworks: Countries vary in progress, with Austria leading in supportive regulations, while Sweden and the Netherlands are still in early stages.
- Governance and operational models for energy communities focus on optimizing local energy use and reducing costs through pricing mechanisms, battery scheduling, and innovative trading systems such as blockchain-based and peer-to-peer exchanges to ensure fair benefit distribution.
- Energy sharing optimizes local resource use but faces technical challenges. Grid stability must be maintained to prevent voltage fluctuations. High infrastructure costs also hinder adoption. Blockchain technology enables secure peer-to-peer transactions but poses scalability and privacy issues. Moreover, interoperability challenges arise due to a lack of standardized protocols, which frameworks such as IEEE 2030 and VHPready aim to address this issue.

The review on energy sharing ends us giving recommendations for concrete research activities to conduct in PED StepWise in the coming months. These include analyzing further national regulations around energy-sharing in each living lab, enhancing collaboration through clear stakeholder roles involved in energy-sharing models, assessing financial incentives, and exploring market models such as peer-to-peer trading and blockchain transactions.

Behavioral change among end-users for energy reduction also plays an important role in successfully implementing the PED concept in a neighbourhood.

The review on this topic highlights the impact of various behavioral interventions on energy conservation in past projects, focusing on non-residential buildings. Findings indicate that:

- Using multiple intervention approaches (e.g., social comparison, moral appeals, feedback, public commitment) leads to greater energy savings than single interventions. Also, a higher number of interventions is positively correlated with both immediate and long-term energy reductions.

- Longer intervention durations improve habit formation and enhance both short- and long-term energy efficiency.
- Providing concrete, tailored information about a building's energy systems increases behavioral impact, as many non-residential users are unaware of their influence on energy consumption.
- Changing social norms or attitudes is not necessary for significant energy reductions—information provision alone is more important to drive behavioral change.

Key recommendations drawn from the best practice review on the topic energy behaviour for research activities in PED StepWise involve raising awareness of individual energy behavior impacts in each building, creating feedback structures to provide better information to end-users and facility managers, exploring energy information tools, and promoting local energy conservation as a community goal.

The last topic included in the review concern how to ***overcome organizational and governance challenges through stakeholder engagement.*** This is a critical element to the successful implementation of any energy project in a neighbourhood requiring strong stakeholder engagement, participatory decision-making, and also capacity building. The review highlights key factors for effective collaboration and participation:

- Governance & Coordination: Clear roles, responsibilities, and early stakeholder involvement ensure transparency, trust, and effective collaboration.
- Inclusive & Meaningful Participation: Active engagement, especially of underrepresented groups, should be flexible, fair, and value local knowledge rather than rely on financial incentives.
- Transparent communication: Providing timely, clear, and accessible information builds trust and supports informed decision-making.
- Building trust and acceptance: Citizen ownership, financial participation, and clear communication about project impacts enhance engagement and long-term sustainability.
- Education & Empowerment: Stakeholders need knowledge and training to make informed decisions and maintain solutions beyond the project's lifespan.

To enhance participation in future activities of the living labs in PED StepWise, the report provides recommendations for future activities such as adapting communication formats to end-users, integrating digital and in-person engagement, preventing exclusion of marginalized groups, and showcasing successful projects to encourage involvement.

In conclusion, the best practices identified in this report provide actionable strategies to address energy-sharing challenges, promote behavioral change, and improve governance and participation. These insights will guide future efforts within the PED StepWise project, enhancing the success and scalability of our efforts across the three living labs.

1. Introduction

Europe has achieved notable advancements in building-level innovations, exemplified by the development of Nearly Zero-Energy Buildings. Currently, there is a shift from building solutions towards city-wide transformation. An example is the concept of Positive Energy Districts or neighborhoods, also known as PEDs, which builds upon the smart cities' paradigm. The PED concept is part of a European initiative ("the European SET Plan Action 3.2") that aims to realize 100 PEDs by 2025, under the leadership of JPI Urban Europe.

The PED definition is still under discussion and can vary depending on system boundaries, calculation methodology of energy balance, and the established KPIs (Mattsson et al., 2023; Uspenskaia et al., 2021). A common definition used across different studies is as follows:

Positive energy districts (PEDs) are defined as: "*Energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability districts* (Sassenou et al., 2024).

Based on previous experiences with PED projects in existing areas, the **PED StepWise** project aims to address the challenges around the decarbonization of existing buildings at the district level.

To achieve the abovementioned overarching goal, a key step in the project is to learn from existing practices that can help overcome the present challenges in the living labs part of PED StepWise to achieve CO2 emission reduction and ultimately PED implementation. This report, part of Work Package 2 of the PED StepWise project, describes the results of a review of best practices in three different topics. The topics aligned with existing challenges found during the Stakeholder Analysis in the three living labs of Vienna, Malmo, and Utrecht, which has also been conducted as part of Work Package 2 of PED StepWise. The goal of the present review is to identify actionable strategies, innovative approaches, and lessons learned in other projects that may help tackle some of the main challenges experienced in the three livings.

2. Methodology

The literature review followed various key steps:

1. **Topic Selection** – Three topics were identified for investigation in the best practices review. This selection resulted from two co-design sessions with various research team members across the three living labs. The topics were chosen based on their relevance to the living labs (e.g., alignment with existing research questions or challenges) and their applicability in multiple contexts (i.e., relevant to at least two or three living labs, rather than just one). The final selection included three topics, each with associated research questions, as outlined in Table 1.

2. **Search strategy & Literature identification** – Each topic was assigned to a designated researcher responsible for conducting the literature review. Before starting, the researchers agreed on a common approach to ensure consistency. This included generating keywords based on the topic, developing search strings using Boolean operators (AND, OR, NOT), and searching for relevant literature across three academic databases: Scopus, Web of Science, and Google Scholar (Table 2). Additionally, grey literature (e.g., project reports and non-scientific publications) of PEDs and decarbonization projects was considered where relevant.
3. **Screening & Selection of publications** – An initial screening of titles and abstracts was performed to remove irrelevant publications that did not align with the research question or focus on unrelated subjects. Articles published before the year 2000 were also excluded. A full-text review was later conducted on the remaining articles to ensure alignment with the research questions. For each topic, up to 10 papers were selected for the final analysis. This number was chosen to maintain a manageable dataset for an in-depth literature review while ensuring meaningful insights could be extracted without exceeding the resources allocated for this task within WP2.
4. **Adding further examples beyond the literature review** – Next to the literature review, we also collected examples of PEDs and decarbonization projects through online research that they were helpful examples for the analysis.
5. **Analysis & Synthesis of results** – The selected papers and projects were in-depth studied and analyzed. The analysis led to a summary of key findings, paying attention to lessons learned, methodologies, and approaches relevant to the topics and living labs in the PED StepWise project.

For one of the selected topics, Figure 1 illustrates a summary of Steps 2, 3, and 4 as an example.

Table 1 The three studied topics in the best practices review

Topic	Research questions per topic	Relevant to living lab
Energy sharing	-What can we learn from other communities in terms of energy sharing between buildings? -Which practices (technical, organization, regulation) are transferable / are not to our living labs?	Malmo, Utrecht
Reduce energy demand of end-users (energy behaviour)	-What are successful methods in changing behaviour of end-users to reduce energy in non-residential buildings? -Which have been the lessons learned, main challenges and ways to overcome these?	Malmo, Utrecht
Overcoming organizational and governance challenges in the decarbonization of a community	-How can stakeholder engagement be optimized to facilitate the decarbonization process (location: science parks and residential areas), considering the diverse interests and decision-making of various stakeholders (building owners, tenants, management, local authorities)? -What practical solutions and strategies can be applied to other contexts?	Malmo, Utrecht, Vienna

Table 2 Strings used in the search strategy for each topic in the literature review and number of results per database

Topic	Strings used	Number of results per database
Energy sharing	**Web of science**: TS=("energy sharing" AND "energy communities" AND (barrier OR advantage OR challenge OR benefit OR regulation OR polic)) **Scopus**: TITLE-ABS-KEY("energy sharing" AND "energy communities" AND (barrier OR advantage OR challenge OR benefit OR regulation OR polic)) AND PUBYEAR	Web of science: n=49 Scopus: n=90-44 (Duplicates)=44
Reduce energy demand of end-users (energy behaviour)	**Web of Science**: TS= ("case stud*" OR "best practice*" OR "lessons learned" OR challenge* OR solution* OR interven*) AND TS= ("energy efficiency" OR "energy reduc*" OR "energy sav*" OR decarbon* OR "energy conservat*" OR (Energy NEAR/5 (Neutral* OR Positive))) AND TS= ("behavior* modif*" OR "behavior* chang*" OR "behaviour* modif*" OR "behaviour* chang*" OR engag* OR participat*) AND TS= (students OR staff OR employe* OR "end-user*") AND TS= (Campus OR "Science Park*" OR District* OR Neighbourhood* OR Neighborhood* OR communit*) **Scopus**: ("case stud*" OR "best practice*" OR "lessons learned" OR challenge* OR solution* OR interven*) AND ("energy efficiency" OR "energy reduc*" OR "energy sav*" OR decarbon* OR "energy conservat*" OR (Energy NEAR/5 (Neutral* OR Positive))) AND ("behavior* modif*" OR "behavior* chang*" OR "behaviour* modif*" OR "behaviour* chang*") AND (student* OR staff OR employe* OR "end-user*") AND (Campus OR "Science Park*" OR District* OR Neighbourhood* OR Neighborhood* OR communit*)	Web of Science: n = 68 Scopus: n = 27 Flexible Google Scholar search: n > 1000
Overcoming organizational and governance challenges in the decarbonization of a community	**Web of Science**: (Engag* OR Participat* OR Practice*) AND (Decarboni* OR "Zero-carbon" OR (Energy NEAR/5 (Neutral* OR Positive))) AND (Campus OR "Science Park*" OR District* OR Neighbourhood*) **Scopus**: (participat*) AND (decarboni* OR "Zero-carbon" OR (nergy AND (neutral* OR positive))) AND (campus OR "Science Park*" OR district* OR neighbourhood*) **Google scholar:** (Engagement OR Participation OR Practice) AND "positive Energy" AND (campus OR "science park" OR district OR neighbourhood) → 28.200 documents	Web of Science: n=131 Scopus: n=163 Google Scholar: n>28.000

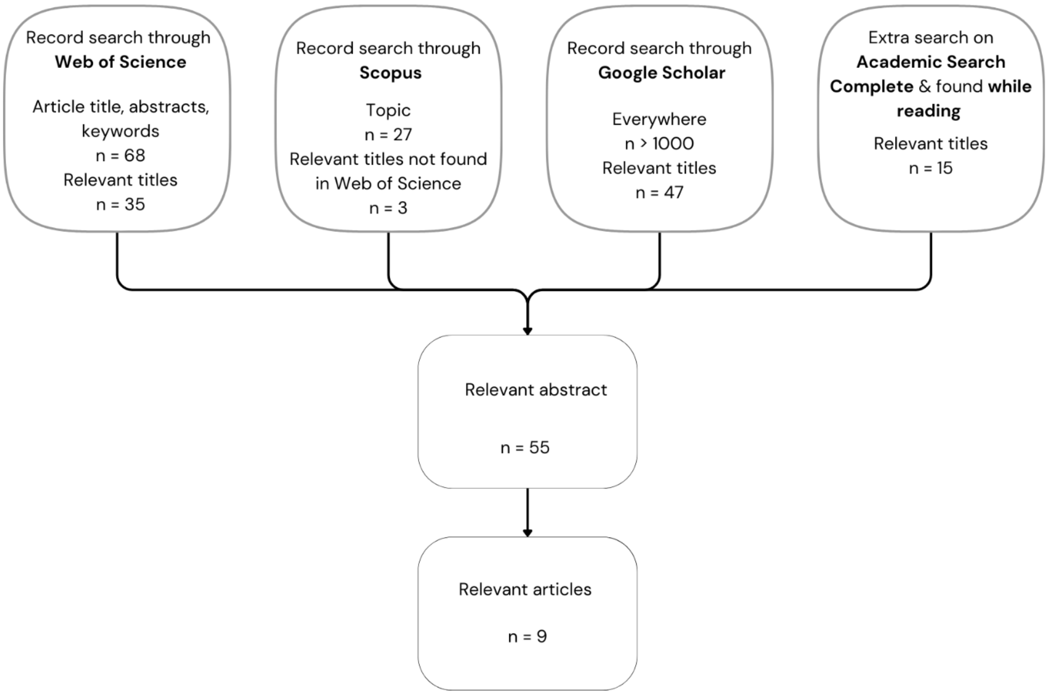

Figure 1 Example of literature search used for topic Reduce energy demand for end-users

3. Results – Insights gained from literature review

3.1. Energy sharing

Energy sharing is a collaborative approach where energy is generated, stored, and exchanged typically within a local community or grid, playing an important role in Positive Energy Districts (PEDs). This concept aligns closely with Energy Communities (ECs), as both share common goals of local energy generation, consumption, and optimization, as well as decentralized renewable energy integration and collective energy management. Energy sharing ensures a more efficient and sustainable system by optimizing energy use, reducing costs, enhancing grid stability, and maximizing renewable energy. Both PEDs and ECs emphasize community-driven energy solutions, reducing reliance on central utilities, minimizing carbon emissions, and promoting self-sufficiency. This decentralized approach supports smart city initiatives and strengthens the transition toward a more resilient and climate-friendly energy future. The growing interest in PEDs and ECs has motivated extensive research across various disciplines, reflecting their potential to transform the traditional energy landscape.

This section categorizes the reviewed literature into three key areas to provide a comprehensive understanding of energy sharing within PEDs and ECs. The first category, Policy and Regulatory Frameworks, examines the legal and policy frameworks that shape the development and functioning of ECs, highlighting challenges and opportunities within different regulatory contexts. In terms of Policy and Regulatory Frameworks, our analysis focuses on three specific countries within our project: Austria, Sweden, and the Netherlands, examining their national policies, regulations, and incentives related to energy sharing. However, our evaluation takes a broader, general approach for the other two categories, considering overarching trends, challenges, and best practices without being limited to specific national contexts. The second category, Governance and Operational Models, focuses on the strategies and models employed to optimize energy sharing, including governance structures, financial mechanisms, and stakeholder coordination. Finally, the third category, Innovative Technologies, explores the advancements in tools and systems—such as smart grids, energy storage, and renewable energy solutions—that enable efficient energy sharing. This approach aims to depict the multifaceted nature of energy sharing and its implications for sustainable energy integration.

3.1.1. Policy and Regulatory Frameworks in Practice

In 2016, collective self-consumption and its organized form through EC concepts emerged in Europe and are legally now regulated by two European directives (European Commissions, (European Commissions, 2018, 2019)). The concept of ECs is established in the recast Renewable Energy Directive (REDII), part of the European Clean Energy Package, which defines "Renewable ECs," and the new Electricity Market Directive (EMD), which outlines "Citizen ECs." These directives provide organizational frameworks and legal opportunities, granting ECs specific rights to participate in energy markets. Additionally, the EMD enhances market access for aggregators and supports the provision of flexibility within the energy system. The EU frameworks also explicitly allow energy sharing within a community, including via the public grid.

ECs are an emerging form of energy production by local producers/prosumers for local communities; they might take many forms, but the main idea is that energy resources are locally managed and controlled by residents and/or local government or businesses. Their primary purpose is to provide environmental, economic, or social benefits rather than financial profits.

The real benefits for local communities and participants depend largely on the national regulatory framework, governance, energy-sharing model, and social aspects. Especially relevant are the legal definition and the corresponding enabling framework of ECs at the national level, potential trade-offs between international market integration and social support, profitable trading models and profit-sharing schemes, entry and exit rules, interaction with other energy market actors, and social acceptance strategies (Mantegazzini et al., 2023).

- Energy Communities (ECs) and self-consumption and sharing are gaining traction in Europe, supported by the Renewable Energy Directive (REDII) and the Electricity Market Directive (EMD).
- While the EU directives provide general frameworks for ECs and energy consumption and sharing, not all EU countries have transposed effectively this new types of initiatives and concepts into national regulation. Their primary goal is to provide environmental, economic, and social benefits, rather than financial profits.
- ECs focus on local renewable energy generation, sharing, and storage, using sources like solar, wind, and hydro.
- Potential benefits include energy security, cost savings, and reduced dependence on centralized power.
- The long-term success of ECs depends on national regulatory frameworks, governance, and social

3.1.1.1. National Legal Framework in Austria

Austria is among the most advanced EU Member States in transposing energy community rules into operational frameworks(RESCOOP.EU, 2022) . The country has implemented detailed regulations to enable energy sharing, including incentives such as reduced grid fees for specific grid usage and feed-in premiums for up to 50% of excess production. While these rules are not without flaws and administrative processes remain complex, they allow energy sharing and are progressively becoming more user-friendly. Austria has also established the Austrian Coordination Office for ECs, an online one-stop-shop that supports ECs and coordinates governmental efforts to create an enabling environment across various levels. Notably, energy-sharing activities can be conducted without requiring a supply license. Overall, Austria's proactive approach to ECs has led to the establishment of numerous ECs, even as the framework continues to evolve and operational insights are gained.

Several organizations have developed tools and services to facilitate energy sharing. An example is eFriends (eFriends, n.d.), an organization founded in 2015 before legal ECs existed. The organization enables users to buy and sell electricity via an app and operates as a business, making it ineligible as an EC; it also leases rooftops for PV installations. Another example is OurPower (ourpower, n.d.), a cooperative with over 250 power plants generating energy from PV (60%), wind (20%), and hydropower (20%), runs two joint ECs and one unregistered CEC while offering a leasing model where rooftop ownership transfers to tenants after ten years. A third example is Grätzl Energie (Grätzl Energie, n.d.), a EC in Vienna managed by Power Solution, operates within a defined geographic area using a common substation and provides leasing models similar to OurPower. Most CEC in Austria remain small, family-run operations, typically limited to sharing PV-generated electricity among relatives.

3.1.1.2. National Legal Framework in Sweden

The regulatory framework governing Sweden's energy system is shaped by EU directives and national legislation, primarily the Electricity Market Directive (EMD) and the Renewable Energy Directive (RED) (The Swedish Energy Agency, 2022). The Swedish Energy Market Inspectorate is responsible for implementing these directives, though ECs have not yet been formally incorporated into Swedish law. However, available data suggests that ECs will be introduced in some forms in the near future (Berggren et al., 2023).

The primary national legislation governing the energy market and the potential implementation of ECs is the Electricity Act (1997:857), which regulates energy generation, conversion, transmission, trading, distribution, and usage in Sweden. It classifies electrical installations based on their hazard levels and environmental impact, and the Energy Market Inspectorate ensures compliance with these regulations. Another key legal framework influencing ECs is the regulation on exemption from network concession (2007:215) (IKN-förordningen, 2007).

Under the Electricity Act, Distribution System Operators (DSOs) manage regional and local grids as monopolies within designated areas, requiring a network concession. However, the regulation on exemption allows for the development of internal networks without concession, provided they are confined to a well-defined area and remain relatively small, such as within a single residential building or factory. This regulation does not currently permit electricity sharing between multiple buildings, limiting the feasibility of ECs that rely on a shared network. Nevertheless, a few pilot projects have been granted exceptions to explore the potential benefits and challenges of EC, including energy sharing development in residential areas.

Despite these initiatives, several legal and practical barriers hinder the widespread implementation of ECs in Sweden. The network concession requirement is a significant legal obstacle, while other challenges include the monopolistic role of DSOs, financial and technical constraints faced by stakeholders, low public awareness, and political and legal uncertainty regarding the definition of ECs (Taleb & Al Farooque, 2021).

There are a few Swedish projects which aim to gain experience through energy-sharing pilots. An example is the Tamarinden project in Örebro, which aims to develop an energy-efficient residential area with 800 apartments across ten buildings, starting construction in autumn 2022. Led by the municipality alongside several construction companies, the project focuses on reducing, producing, storing, and sharing energy within a local system to increase renewable energy use, cut power peaks, and relieve the national grid. Tamarinden seeks to create scalable models for energy transition across municipalities (Municipality of Örebro, 2023). The Tamarinden pilot project has extensively investigated taxation on locally shared electricity since 2020. In March 2023, authorities ruled that its interconnected solar panels formed a single facility exceeding 500 kW, making all shared electricity fully taxable. However, after persistent efforts, including a legislative request by Örebro municipality, the Tax Board ruled in March 2024 that electricity in local networks can be shared tax-free. This allows property owners to install and connect solar panels without taxation, marking a major victory for the project and a model for sustainable urban development across Sweden, including Malmö.

Similarly, ElectriCITY – Hammarby Sjöstad 2.0, a citizen-driven innovation platform in Stockholm, has been working since 2014 to transform the Paris Agreement into local energy solutions, to make the district climate-neutral by 2030. Since 2022, ElectriCITY has been developing a local EC with solar power, a microgrid, and battery storage, helping housing associations implement energy-saving measures while fostering "prosumers" who generate and consume their own electricity (ELECTRICITY, 2022). Meanwhile, the SIMRIS project (2017–2019) demonstrated a 100% self-sufficient energy system in a rural village in southern Sweden, run entirely on renewable energy. As one of six European demonstrators in the EU-funded Interflex project, SIMRIS successfully explored how small communities can operate on renewable energy while enhancing grid flexibility (E.ON, 2022). In SIMRIS, E.ON, as a DSO and service provider, tested and performed simulations of a Peer-2-Peer market by operating the local energy system and the microgrid.

Regarding the energy sharing microgrid technology, a Swedish company Ferroamp, developed EnergyHub direct current (DC) microgrid system for energy sharing within a building community based on the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol. The EnergyHub microgrid system was implemented in a real building community in Sweden (Ferroamp, 2022).

These projects are important from a regulatory perspective because they highlight the challenges and opportunities in implementing local energy communities (ECs) under existing laws. They demonstrate how taxation, grid regulations, and policy support impact energy sharing, self-consumption, and the development of microgrids.

3.1.1.3. National Legal Framework in the Netherlands

In the Netherlands, both governmental and civil society organizations widely acknowledge the potential of ECs as key contributors to the energy transition. This recognition is reflected in the significant number of ECs already established in the Netherlands. Despite this progress, ECs continue to face regulatory and practical challenges when setting up their initiatives. The challenges could be legal or practical barriers. The old Electricity and Gas Laws made energy sharing nearly impossible, except through specific experimental schemes. Currently, members must sell their energy to providers, who then sell it back to the community, adding complexity and reducing direct benefits. In terms of practical barriers, securing upfront investments is challenging due to the reliance on volatile energy prices. Moreover, ECs rely on municipalities, DSOs, and private companies for infrastructure and support. Power imbalances can lead to unequal negotiations.

Recognizing these barriers, a new legislation has been developed to lower obstacles and enhance opportunities for ECs, fostering their growth and impact on the energy transition (NORDIC ENERGY RESEARCH, 2023). The new Energy Law ("energiewet") replaces the Electricity and Gas Acts, aiming to encompass all energy carriers and provide more opportunities for energy sharing within ECs. The law allows peer-to-peer energy sharing via intermediaries and cable pooling (sharing electricity connections among multiple users) (Commissie voor Economische Zaken / Klimaat en Groene Groei (EZ/KGG), 2023), but direct energy sharing (without intermediaries) is still not permitted under the new law (Tiekstra, 2024). Although the law does not currently include an experimentation clause, public consultation has shown support for its inclusion to enable flexibility for innovation. Legal barriers, such as strict regulatory requirements and limited allowances for energy sharing under previous laws, persist, while practical challenges include securing upfront investments, dependency on external actors, and a lack of technical and organizational knowledge. Despite these obstacles, drivers such as high energy prices, active advocacy by the organization Energy Samen, regional energy strategies, and support from DSOs have spurred the growth of ECs.

Energy sharing involves the simultaneous use of locally generated electricity, facilitated by an **energy sharing organizer.** Energy supply is managed by **licensed energy suppliers**. At present, cooperative energy suppliers or energy communities also act as energy-sharing organizers, handling both shared and supplied electricity, but future regulations may allow these roles to be separated, giving energy community members the freedom to choose their supplier independently. The new energy law ("energiewet") introduces the possibility for energy communities to supply energy without a license, providing greater flexibility in contract agreements while still requiring compliance with market processes. Although this change grants more autonomy, fundamental market mechanisms remain intact, with energy service providers continuing to manage surplus and shortage transactions. This self-regulation is a positive step for democratically organized energy communities, making energy sharing and supply more accessible (Local4Local, 2024).

Like Sweden, the Netherlands is also building experience with energy-sharing projects. An example is found in the Cooperative Republica Papaverweg in Amsterdam, which aims to create a sustainable urban community integrating rental and owner-occupied housing, business spaces, and a hotel. The project prioritizes circularity and renewable energy, featuring a smart grid with battery storage to balance local energy supply and demand (Republica, no date). Similarly, the homeowners Association Schoonschip is developing 46 floating homes in North Amsterdam, designed to be self-sufficient through an advanced smart grid. This system is being developed in collaboration with research and private institutions (Schoonschip, no date). Local4local project develops bottom-up solutions for energy supply at area level, with an eye for inclusive and social-societal design principles. These solutions include smart collective energy services by ECs for residential areas and business parks, local system integration, and tools and methods for the design of a local energy system (Local4Local, 2023). They used ENTRNCE Trader is an innovative platform that enables participants to conduct peer-to-peer transactions and actively participate in various energy markets. The platform facilitates direct transactions between producers and consumers, allowing users to trade energy at the level of individual connections (ENTRANCE, 2024). The BioZon pilot demonstrates how energy sharing is already being implemented, with electricity from a biogas plant distributed among members, supported by multiple energy service providers and grid operators through the Entrnce platform for balancing consumption and generation. As part of the Local4Local program, the pilot underscores the importance of collaboration between cooperative suppliers and service providers, with the future development of a unified energy sharing organizer expected to further strengthen cooperative energy models (Local4Local, 2024). In Sporenburg, a neighbourhood in Amsterdam's Eastern Docklands (Reschool, 2024), 80 out of 500 households are working together in an energy community called FlexCitizen (FlexCitizen: a Research project, 2024) to balance electricity use. Residents are equipped with smart meters and an app that provides real-time insights into their energy consumption. The app offers challenges and incentives to encourage flexible energy use.

- Austria is a leader in energy community implementation, with well-developed regulations allowing energy sharing, reduced grid fees, and a supportive one-stop-shop for energy communities. Despite administrative complexities, numerous energy communities implementing energy-sharing practices have been successfully established.
- Sweden is in the early stages of energy sharing and energy community development, with no formal legal framework yet, but pilot projects like Tamarinden and ElectriCITY are exploring scalable models. Key legal barriers include network concession rules, monopolistic DSOs, and regulatory uncertainty.
- The Netherlands acknowledges the role of energy communities in the energy transition and has many ECs in place, however, energy sharing is in its early stages. There are regulatory and practical challenges that remain. A new Energy Law has been developed to facilitate energy sharing, while several projects like Local4Local, Schoonschip, and Republica Papaverweg demonstrate innovative energy models that aim to facilitate energy sharing and self-sufficiency.

3.1.2. Governance and Operational Models

Energy management models for EC have been studied in the literature. For instance, Liu et al. (Liu et al., 2017) proposes **a model for scheduling shiftable loads based on an internal price** computed from the supply-to-demand ratio (SDR), assuming uniform retail and feed-in tariffs among all prosumers (as the SDR is otherwise undefined). In this approach, the community manager determines selling and buying prices for each delivery time, considering the SDR and the prosumer's selling or buying position. Each prosumer then minimizes their energy bill, accounting for an inconvenience cost associated with load shifting, resulting in an equilibrium problem solved iteratively.

Similarly, Long et al. (Long et al., 2018) presents a **two-stage model to minimize the energy costs** of a renewable energy community (REC) by centrally managing its members' battery schedules. The model realizes P2P energy sharing in community microgrids, where only the measurement at the point of common coupling (PCC) and one-way communication are required. This method allows individual prosumers to control their distributed energy resources via a third-party entity, so-called energy sharing coordinator. In the first stage, a constrained non-linear programming optimization with a rolling horizon was used to minimize the energy costs of the community. In the second stage, a rule-based control was carried out updating the control set-points according to the real-time measurement. The benefits of P2P energy sharing were assessed from the community's as well as individual customers' perspective. The proposed method was applied to residential community Microgrids with photovoltaic (PV) battery systems. It was revealed that P2P energy sharing is able to reduce the energy cost of the community by 30% compared to the conventional peer-to-grid (P2G) energy trading. Furthermore, Zhang et al. (Zhang et al., 2019) explores a peer-to-peer (P2P) market structure that incorporates dynamic retail electricity prices to automate bid generation within the community. In addition to using SDR, this study evaluates the effectiveness of Double Auction (DA) and Mid-Market Rate (MMR) pricing models, providing comparative insights into their performance.

Various strategies for **energy management in microgrids and ECs** have been explored. In a recent study (Ruiz-Cortés et al., 2019), a genetic algorithm optimizes battery schedules to reduce energy exchange losses with the main grid. Energy sharing among batteries in the community is scheduled to minimize the power imbalance between forecasted generation and load and planned storage during the 24 hours of a one-day time horizon. Zhou et al. (Zhou et al., 2020) integrates local energy markets and flexibility services, while Heer et al. (Heer et al., 2017) emphasizes using baseline methods to calculate delivered flexibility.

In the study of Putratama (Putratama et al., 2023), a three-stage strategy under French self-consumption regulation minimizes energy bills, mitigates uncertainties, and maximizes community-wide benefits. Another study (Cornélusse et al., 2019) introduces **a two-level model that maximizes local market welfare and ensures fair profit-sharing**, accounting for reserve capacity and peak power tariffs at the community level. Finally, Yahaya et al. (Yahaya et al., 2020) proposes a blockchain-based peer-to-peer trading system, incorporating **Critical Peak Pricing (CPP) and Real-Time Pricing** (RTP) to reduce costs while maintaining security and privacy.

Few studies address the integration of grid flexibility provision with local energy management systems or markets to alleviate potential constraints in the local distribution grid connecting community members. An exemplary study (Rocha et al., 2023) introduces a **three-stage model** to address this gap. In the first stage, the model minimizes the individual energy bills of members in an EC. The second stage minimizes the REC's collective bill by redistributing internal energy surpluses while ensuring no member's individual bill increases, thus promoting a fair allocation of the REC's collective benefits. In the third stage, the model resolves grid constraints by activating local flexibility measures, such as battery dispatches or, when necessary, load and generation curtailments, while minimizing the cost of these flexibility activations. Consistent with EU wholesale market practices, financial transactions are settled independently of the dispatches required to address grid constraints. The schematic representation of the three-stage model is presented in Figure 2. To validate the proposed methodology, the IEEE 14 bus test case (Zhao et al., 2009) was used.

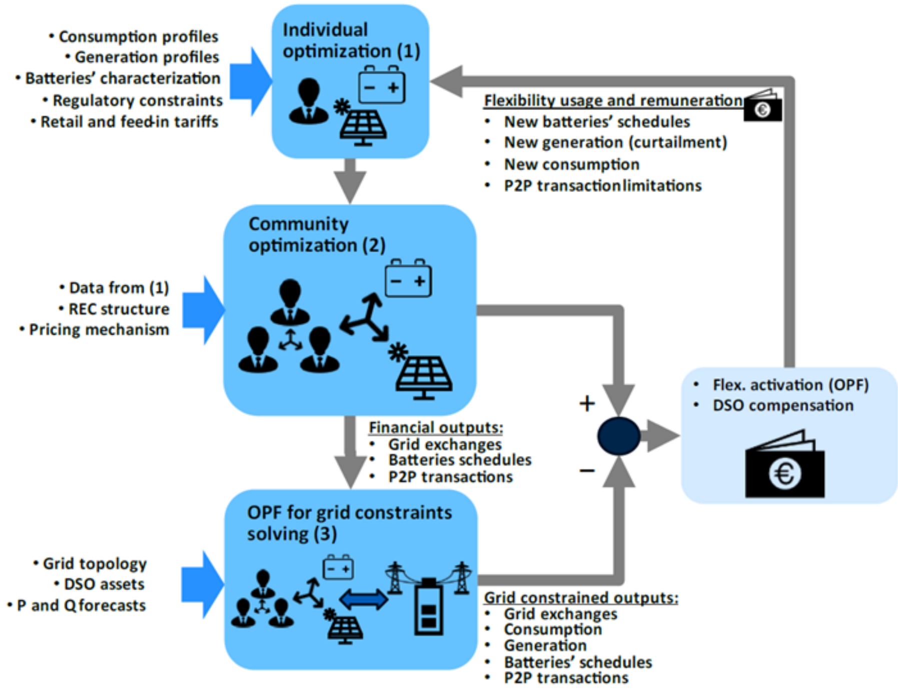

Figure 2: Three-stage energy management model (Rocha et al., 2023)

Dhorbani et al. (Dhorbani et al., 2023) introduce an innovative approach to optimizing energy exchanges within local ECs using a **private blockchain framework** (seeFigure 3). The proposed system harnesses the advantages of blockchain technology—such as decentralization, immutability, and transparency—to overcome the limitations of traditional energy management systems. The approach is designed to optimize energy transactions between energy community members while accommodating individual preferences and objectives.

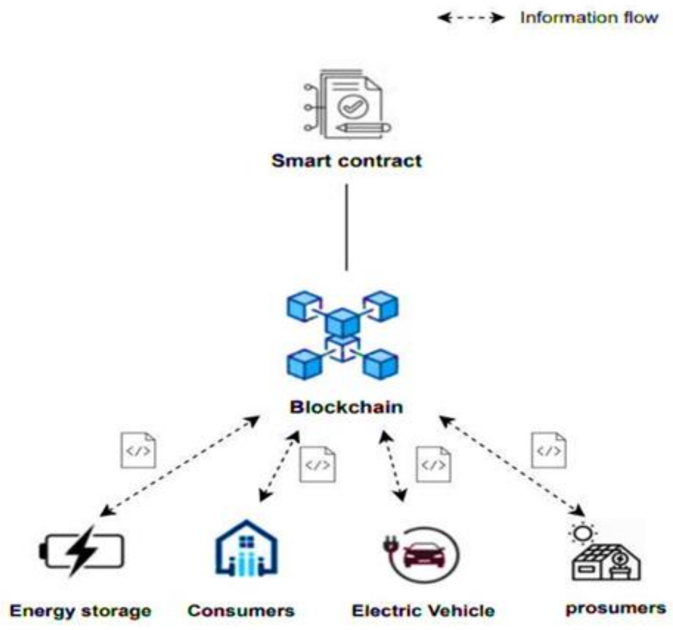

Figure 3: Blockchain-Based Energy Community (Dhorbani et al., 2023)

To evaluate the proposed private blockchain framework in a realistic scenario, an study (Dhorbani et al., 2023) utilizes the grid demonstrator at Lille Catholic University (see Figure 4), which serves as an exemplary model of a local EC.

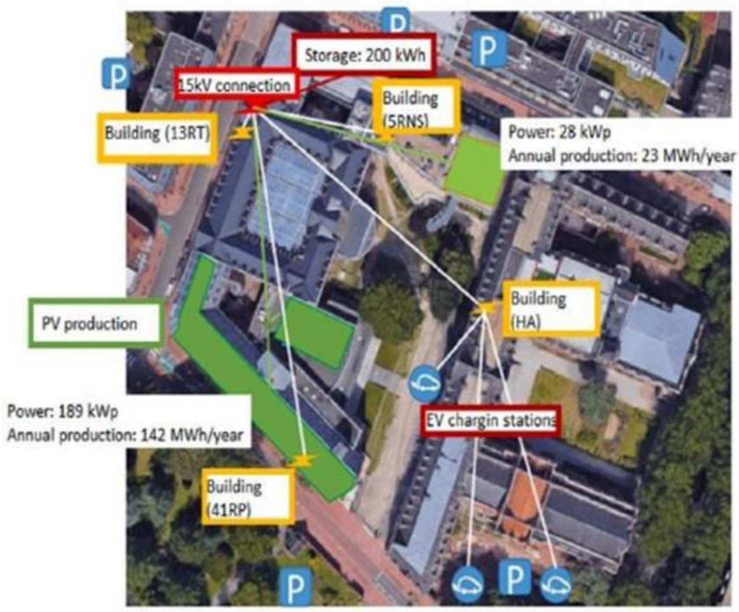

Figure 4: Lille Catholic University demonstrator grid (Dhorbani et al., 2023)

As shown in Figure 5, each user defines their type, such as building, electric vehicle, storage system, or PV generator, and specifies their preferences using coefficients ranging from 0 to 1. These preferences include factors like comfort, cost considerations, and the willingness to consume locally produced electricity.

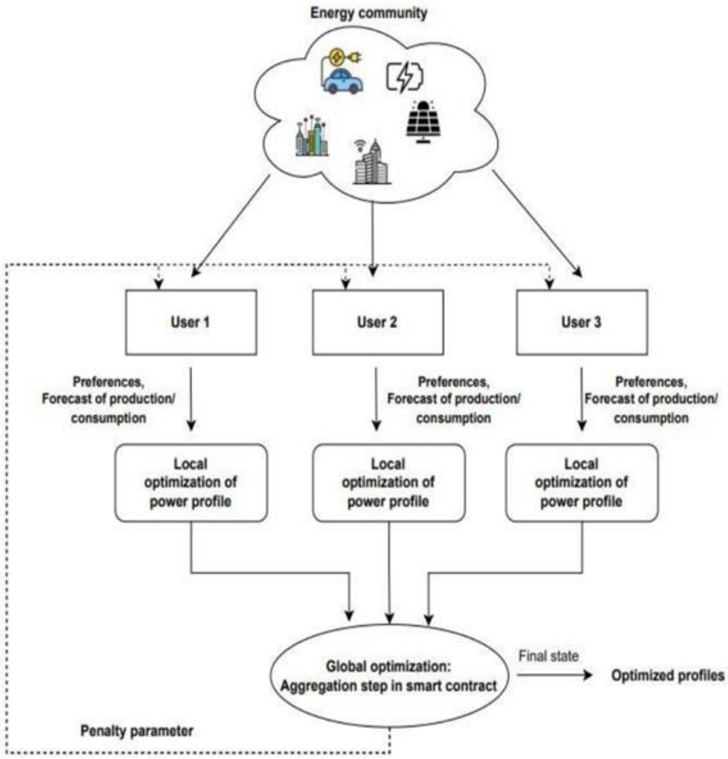

Figure 5: Optimization method for energy exchanges within local ECs using a private blockchain framework (Dhorbani et al., 2023)

- Various energy management models, such as **pricing mechanisms** based on supply-to-demand ratios and battery schedule optimizations, are being developed to reduce energy costs and optimize local energy use within these communities.
- Innovations like **blockchain-based** and **peer-to-peer trading** systems and strategies to address grid constraints are being explored to enhance energy exchanges and ensure fair distribution of benefits within energy communities.

Table 3: Reviewed literature on the topic Operational Models for energy sharing

Reference	Operational model	Key Features	Outcomes	Challenges
(Liu et al., 2017)	Price-based demand response model for energy sharing among peer-to-peer (P2P) PV prosumers in a microgrid	Dynamical internal pricing model based on the supply-to-demand ratio (SDR) of shared PV energy	More economical energy sharing compared to independent prosumer operation, Reduction in PV prosumers' costs, Improved utilization of shared PV energy	Dependency on SDR for internal pricing, which may introduce volatility, Ensuring fair cost distribution among prosumers
(Long, Wu, Zhou, & Jenkins, 2018)	Two-stage aggregated control for P2P energy sharing in community Microgrids First stage: Constrained non-linear programming (CNLP) optimization with a rolling horizon to minimize community energy costs -Second stage: Rule-based control for real-time adjustment of set-points	Minimal sensing and communication requirements (measurement only at PCC, one-way communication) Energy Sharing Coordinator (ESC) manages DERs for prosumers	Consumers' electricity bills reduced by ~12.4% Prosumers' annual income increases by ~£57 per premises Pricing mechanism ensures fair economic benefits for all participants	Requires intensive sensing and communication infrastructure for real-time coordination Existing P2P pricing mechanisms may not guarantee economic benefits for all participants Coordination via a third-party entity (ESC) introduces potential complexity and reliance on external control
(Zhang et al., 2019)	P2P energy trading framework integrating dynamic retail electricity pricing	Allows prosumers to trade surplus PV-generated electricity with neighbors Uses a decision-making model for bid automation	Economic benefits for participants Improved local energy balance	Need for robust automation and real-time data exchange Regulatory and technical barriers for implementation

		Evaluates three pricing models: Double Auction (DA), Mid-Market Rate (MMR), and Supply and Demand Ratio (SDR)	Effective demand response and distributed generation management	
(Ruiz-Cortés et al., 2019)	Coordinated energy scheduling using a genetic algorithm to optimize battery charge/discharge cycles and energy sharing among batteries in a microgrid of prosumers.	Integration of photovoltaic (PV) systems, Li-ion batteries, and household loads. Focus on minimizing power exchange with the main grid to reduce energy losses. Comparison of individual vs. coordinated energy strategies.	13% reduction in energy exchanged with the main grid.	Dependence on forecasting accuracy for PV generation and consumption patterns. Potential computational burden of genetic algorithms for real-time applications.
(Putratama et al., 2023)	Three-stage energy management strategy for a local energy market under the French collective self-consumption framework.	Households coordinate with a community manager to optimize energy bills for the next day. Mitigates forecast uncertainties and voltage violations using local production/storage reserves. Energy is fairly distributed every 30 minutes per French regulation, ensuring fair cost reduction and potential economic surplus.	Achieves an average 30% reduction in individual energy costs.	Managing forecast uncertainties in real-time. Ensuring voltage stability in the LV grid.
(Yahaya et al., 2020)	Blockchain-based peer-to-peer (P2P) Local Energy Market	Decentralized energy trading without a third party	Economic benefits at both community and individual levels	Dependence on consumer participation for load shifting Complexity of integrating Home Energy Management and demurrage

		Home Energy Management (HEM) system for optimizing energy consumption Demurrage mechanism to encourage efficient energy use		mechanisms into existing energy markets
(Rocha et al., 2023)	A three-stage energy management model for local energy sharing and grid flexibility services. Each stage progressively optimizes energy costs and grid stability while ensuring fair benefit distribution among prosumers.	Stage 1: Minimizes individual prosumer energy bills by optimizing flexible resource schedules. Stage 2: Optimizes the collective energy bill by sharing energy surpluses and re-dispatching batteries, ensuring no prosumer is worse off than in Stage 1. Stage 3: The DSO resolves grid constraints by further re-dispatching flexible resources and, if needed, curtailing generation/consumption with financial compensation. Settlement mechanisms define allocation coefficients for self-consumption and supplied energy calculations.	Ensures fair and efficient energy sharing within communities. Provides additional collective benefits without disadvantaging individual prosumers. Enhances grid stability by using community flexibility resources before enforcing curtailment. Demonstrates potential benefits of negative allocation coefficients to boost market competition.	Ensuring fairness in internal price setting and collective benefit distribution. Managing financial compensation when grid constraints require interventions.
(Dhorbani et al., 2023)	A novel approach to optimize energy exchanges in local ECs using a private blockchain environment. This system leverages	Focuses on optimizing energy exchanges while respecting individual preferences and objectives.	The proposed system facilitates effective energy optimization in local ECs.	The system uses a lot of computer power to run the blockchain operations. This is measured by something called "Gas spent," which

	blockchain technology to address challenges in traditional energy management systems.	Provides comprehensive guidelines for developing blockchain-based applications for energy optimization.		shows how much work the computers are doing.

3.1.3. Technical Outlook for Energy sharing

While energy sharing maximizes the use of locally available resources, its implementation faces several technical challenges. Ongoing pilot projects are testing potential solutions.

Energy-sharing systems must maintain grid stability by balancing supply and demand in real time. **Uncoordinated energy flows can lead to voltage fluctuations, increased grid stress, and inefficiencies.** The Franklin pilot in Tennessee, United States, launched in 2024 by Ara Ake in collaboration with Climate Connect Aotearoa and Counties Energy, is testing a combination of Multiple Trading Relationships and community battery storage to address this issue. By storing excess solar energy and redistributing it when demand peaks, the project helps flatten energy supply fluctuations, improving grid resilience while ensuring a stable and efficient energy-sharing network (Climate Connect Aotearoa, 2024).

Energy-sharing systems **rely on expensive infrastructure, including solar arrays, battery storage, smart meters, and upgraded distribution networks**. These high capital costs pose a significant barrier to widespread adoption. To address this, government-backed funding initiatives, such as the Māori and Public Housing Renewable Energy Fund in New Zealand, have played a crucial role in financing pilot projects. One example is the 2022 partnership between Ara Ake and Kāinga Ora in Auckland, New Zealand, which enabled tenants in Lower Hutt and Porirua to share surplus solar energy. By allowing social housing tenants to sell excess energy at the best available feed-in tariff, the project demonstrated how financial incentives can help monetize energy-sharing models while reducing costs for low-income communities (Climate Connect Aotearoa, 2024).

Large-scale energy-sharing initiatives require collaboration among technology developers, energy retailers, distributors, and government agencies. Without clear roles and integration strategies, implementing such systems can be complex. The pilots across Aotearoa in Auckland, New Zealand illustrate the importance of decentralized energy models where local communities and social agencies take an active role. For example, Kāinga Ora's project involved solar installation and also created a financial model where the revenue from shared energy was reinvested in further renewable installations for low-income households. Such collaborative approaches ensure that energy sharing delivers economic and social benefits to the community (Climate Connect Aotearoa, 2024).

Another technical challenge in energy sharing is ensuring transparent, secure, and efficient peer-to-peer transactions without relying on a centralized intermediary. Traditional energy markets often require third-party oversight, which can introduce inefficiencies and additional costs. To address this, **blockchain technology offers a decentralized solution by automating energy trading through smart contracts**, ensuring secure and tamper-proof transactions (Andoni et al., 2019). Blockchain technology offers secure and decentralized transaction validation for P2P trading, but **it also presents challenges related to scalability and privacy** (Junlakarn et al., 2022). Public blockchains can expose transaction details, compromising user privacy, while high computational requirements can lead to inefficiencies and excessive energy consumption. A shift towards more energy-efficient consensus mechanisms, such as Byzantine Fault Tolerance (BFT) (Ghosh et al., 2022), can significantly reduce energy consumption compared to traditional mining-based systems like Bitcoin.

Furthermore, a problem that arises when integrating different technologies, such as renewable energy systems, storage units, and smart meters to enable energy-sharing is the **lack of standardized protocols, leading to interoperability challenges**. Implementing widely recognized standards like IEEE 2030 and VHPready can enhance interoperability in energy-sharing systems. IEEE 2030 (IEEE SA, 2022) provides guidelines for smart grid interoperability, addressing the integration of energy technology and information technology with electric power systems and end-use applications. Similarly, VHPready (EUREF Campus Berlin, 2024) is an open industry standard designed to control decentralized power generation plants, consumers, and energy storage systems via a central control center, facilitating the flexible connection of these components to virtual power plants and smart grid applications.

- Unbalanced supply and demand cause voltage issues. Community battery storage smooths fluctuations (e.g., Franklin pilot).
- Solar, storage, and smart meters are expensive. Government funding (e.g., Māori and Public Housing Renewable Energy Fund) supports adoption.
- Lack of clear roles complicates implementation. Decentralized models (e.g., Kāinga Ora project) ensure community benefits.
- P2P trading needs transparency without intermediaries. Blockchain enables automated, secure energy transactions.
- Interoperability issues arise from non-standardized systems. Standards like IEEE 2030 and VHPready improve compatibility.

3.2. Reduce energy demand through energy behaviour

The energy behavior of end-users and building occupants plays a key role in implementing PEDs and reducing energy consumption at an organizational level (Dietz et al., 2009; Dixon et al., 2015). Energy use interventions can apply to residential and non-residential settings. Two of the living labs of PED StepWise (Malmö and Utrecht) take place in a non-residential setting. When aiming to address the occupants' energy behavior in non-residential or institutional buildings face unique challenges compared to the residential sector (Carrico & Riemer, 2011; Charlier et al., 2021; Dixon et al., 2015). First and foremost, the building occupants are not financially invested in their energy use on location. Therefore, pecuniary motivation to reduce energy consumption is lacking. Second, feedback and information on current energy use do not reach the end users, further reducing the understanding of having a stake in the buildings' energy efficiency. Third, the provided energy systems and electrical equipment are used by many people at once, leading to a lack of individual responsibility for energy conservation. Fourth, building occupants only have limited control over systems that regulate Heating, Ventilation, and Air Conditioning (HVAC) due to their central management (Sanguinetti et al., 2017).

These challenges have been addressed to various extents in comprehensive studies on energy conservation in universities, research institutes, or company sites during the past two decades (Carrico & Riemer, 2011; Charlier et al., 2021; Dixon et al., 2015; Ramallo-González et al., 2022) (see Table 4). The intervention methods employed range from smart energy systems to comparative feedback methods and informational campaigns. The literature coincides with one another in its concrete testing of existing theories and energy-saving conceptions in large building districts and their outcomes of enhanced energy conservation on-site. As the methods of intervention characterize the main distinction between the studies, this section aims to evaluate and compare the respective intervention success with an analysis of the main lessons learned, including emerging challenges and the best practices. This literature review investigates the research question: What can we learn from other communities in non-residential buildings in changing the behavior of end-users to reduce energy?

The nine main reviewed studies summarized in Table 4 were found to hold six main lessons learned which form a valuable foundation for future research on PEDs and energy conservation intervention implementation in building districts. These lessons are elaborated on in the following with reference to the studies' methods and outcomes. When introduced first, the study's method and extensive results are explained. When referred to later again, the study's contextual elements are delineated, and only the results relating to the lesson learned are elaborated on. The six lessons broadly structure this review into six sub-sections:

1. The more interventions, the better, in the short-term and in the long-term.
2. The longer the interventions, the better.
3. The more concrete the information provided, the better.
4. Norm changes are not required for energy conservation.
5. Smart energy systems are vital in increasing energy efficiency.
6. Gamification is related to increased occupant engagement.

Table 4: Reviewed literature on the topic of energy reduction interventions in buildings

Publication	Building Type	Country	Intervention Method	Duration	Energy Type	Outcome
(Charlier et al., 2021)	47 company sites in the service sector (average of 21 employees and 515 m²)	France	Nudges for energy saving employing a moral appeal in weekly messages (1), social comparison to other firms in weekly reports (2), stickers with information on direct conservation practices (3)	12 weeks (Jan - Apr 2017)	Heating and electricity consumption for other purposes (ventilation, lighting, power, etc.)	Individually, none of the nudges significantly affect energy consumption; Moral appeal with stickers negatively affect electricity use and heating; Social comparison with stickers negatively affect electricity consumption
(Carrico & Riemer, 2011)	24 university buildings with office, teaching, and research spaces	Southern USA	Weekly informational postcards on energy saving; additionally, one group received peer education through a volunteer (1), monthly feedback emails on the building's energy use (2), or all interventions combined (3)	4 months (Sep-Dec 2008)	Electricity use in kWh	All interventions resulted in significant energy reductions; the peer education, feedback, and combined interventions led to reductions of 4%, 7%, and 8% respectively
(Burns & Savan, 2018)	Off-campus student residence with private apartments	Toronto, Canada	Six tailored interventions applied monthly on participant commitment, cooling-, lighting/ electricity-, heating-, laundry/ water-, elevator use-awareness; 7-months intervention follow-up	6 months, Sep 2010-Feb 2011	Energy conservation behaviors at home	Increasing occurrence of conservation behaviors during the intervention, elevated levels seven months after the intervention; no effect on norms or perceived importance of energy conservation
(Dixon et al., 2015)	Six mixed-use (research,	Ithaca, NY, USA	Competition-based comparative feedback through an online tracking	1 year (Dec	Electrical energy	Average of 6.5% decrease in electrical use in the competition buildings

	teaching, academic) university buildings		tool (1), a website (2), and posters (3)	2010-Nov 2011)	consumption in kWh/ft²	
(Ornaghi et al., 2018)	Five office buildings at a university with natural ventilation and space heating	South-ampton, UK	Emails to motivate energy conservation with general information about energy waste of open windows (1), feedback on left-open windows in the building (2), personalized comparison with other occupants on left-open windows (3)	4 months (Sep 2016-Jan 2017)	Heating system energy in kWh/ m^2	Around 50% less windows are left open, especially when tailored information is provided on local consumption (2) and social comparison (3); the effects are persistent multiple weeks post-intervention
(Timm & Deal, 2016)	Four buildings in four different community college campuses	Illinois, USA	Energy behavior change campaign through a central display of real-time energy use in the buildings and educational information	60 days, Sep – Nov 2013	Electricity; Natural gas	Significant energy reductions in electricity and in natural gas; no self-reported changes of attitudes or behavior
(Sanguinetti et al., 2017)	Over 100 university campus buildings with a priority for buildings with a Building Automation	Davis, CA, USA	University web portal and web app, TherMOOstat, to submit thermal feedback for a specific location on campus which is cross-referenced with BAS data; TherMOOstat as a proactive efficiency initiative	23 months (Sep 2014-Jul 2016)	Heating, Ventilation, and Air Conditioning (HVAC)	Improvements in energy efficiency and occupant comfort through on-site equipment fixes (e.g. set points), on-site physical fixes, or BAS reprogramming after feedback receipt

	System (BAS)					
(Dorokhova et al., 2021)	Two building sections of a research institute (around 400 users daily, in Porto); 30-40 residential households (in Lippe)	Porto, Portugal; Lippe, Germany	A set of applications that facilitates best practices for energy efficiency (e.g. Unsupervised occupancy forecast, Tertiary load disaggregation, Automation manager, Behavior predictor)	7 months testing periods (Aug 2019- Mar 2020)	Heating, Ventilation, and Air Conditioning (HVAC)	Forecasting occupancy accuracy of 97.6 %; Near-optimal day-ahead ON/ OFF schedule for HVAC system (potential energy savings of 25.3%); detection of energy saving opportunities while ensuring comfort
(Ramallo-González et al., 2022)	Four offices/ set of laboratories in three connected buildings at a university	Murcia, Spain	An IoT platform/ app that informs about energy use and people's comfort through visualizations and real-time recommendations on energy savings	Two weeks in summer and in winter 2017	Energy data on heating and electricity	Average energy savings of 20%, increase in energy literacy and behavior

3.2.1. The more interventions, the better

One overarching outcome of more than half of the reviewed studies was that **a higher number of different intervention approaches is related to higher overall energy savings**. The interventions differ in their approach by which energy behaviors are pursued to be changed. Common methods, for example, entail elements of social comparison, an appeal to common morality, direct or comparative feedback, or public commitments. Studies testing their separate vs their combined application found that combined applications were consistently related to higher energy conservation than the separate applications. This positive association can be understood from a short-term and a long-term perspective. The former concerns direct positive outcomes through the combined interventions, while the latter implies the lasting persistence of increased energy conservation after the interventions were stopped.

3.2.1.1. The more interventions, the better in the short-term

Demonstrating a **positive correlation between intervention number and direct energy reduction**, three key studies were identified. Charlier et al. (2021) examined the impact of motivational nudges on the energy consumption of employees of 47 companies. In the first implementation phase, the intervention groups received either email messages that encouraged pro-environmental behavior through various means: 1) moral appeals ; (2) social comparison through information on their own and other companies' energy use , and 3) visual prompts in the form of stickers depicting ways to save energy during day-to-day activities. During the second implementation phase, the moral appeal group and the social comparison group both received the visual prompts in addition to the initial intervention, marking a combined intervention.

In the first implementation phase, no significant effect of any of the interventions on energy consumption was present (Charlier et al., 2021). In the second implementation phase, the moral appeals with the visual prompts was significantly negatively related to electricity and heating use, that is, electricity and heating use went down. Less effective but still significant, social comparison coupled with visual prompts led to a decrease in electricity consumption, while heating use was not affected. This points toward the need for simultaneous intervention application for the occurrence of significant effects on energy conservation.

Further clarifying this relation, Carrico & Riemer (2011) conducted an intervention by which university staff and faculty employees received weekly postcards including information on why and through which behaviors energy use could be reduced with the goal of saving at least 15% in every university building. The first intervention group received additional monthly e-mails providing feedback on the energy consumption of their building. The second intervention group was educated by trained peers, in addition to the postcards, through emails on building-specific conservation information and substantiating the postcards. The third intervention group received all treatments at once.

Monthly group-level feedback and peer education both resulted in a significant energy reduction in the buildings (7% and 4% respectively compared to baseline) (Carrico & Riemer, 2011). The combined interventions led to energy reductions of 8%. Even though the calculated energy savings of the combined intervention were not as high as the added savings of the separate interventions, it can be concluded that every intervention approach addresses energy behavior in a unique manner which results in unique energy savings. As the differences between the group-level feedback and the combined interventions group is rather small, further research needs to assess the precise effects of separate and combined intervention apporaches to draw more concrete conclusions about the advantage of combined intervention use.

Third, the aim of Dixon et al. (2015) was to explore the effects of comparative feedback within a year-long energy reduction competition between six university buildings. The feedback was provided to the participants via three platforms. The first one was an online interactive tracking tool by which participants could commit to individually adapted energy conservation activities and register these on a weekly basis. Second, a website was built that portrayed detailed information on the projected savings, the up-to-date ranking of the participating buildings according to energy savings, and participant engagement. Third, posters were hung in busy areas of the building depicting monthly competition data. The participants included the university's faculty, staff, and graduate students. The total energy consumption was measured in kWh/ft² for the year prior and during the competition.

From 2009 to 2012, there was a significant increase in self-reported behavior for energy reduction in the participating buildings compared to the control buildings (Dixon et al., 2015). Across the competing buildings, an average energy decrease of 6.5% from before to after the intervention could be measured while the control buildings that did not participate in the competition experienced an average increase of 2.4% in energy use. This energy use increase in non-competition buildings is not explained. While the impact of the three intervention platforms was not assessed separately, it was evident that their simultaneous application contributed to the decisively positive outcome.

3.2.1.2. The more interventions, the better in the long-term

In addition to Dixon et al. (2015), two more studies highlight the **positive association between intervention number and persisting energy reduction after intervention termination**. While Dixon et al. (2015) found a significant direct energy reduction from before to after a year-long building competition, one year after the intervention, 2012, energy use was assessed once again. They found that the competition buildings increased their energy use by 3.4% on average. Even though an increase did occur, the electrical use levels were still 3.2% below those of the year before the intervention and, compared to the intervention year, the non-competing buildings increased their energy consumption by 10% in 2012. The positive effects of a multi-faceted intervention, in this case, faded with time. However, this happened slowly and with a lasting distinction to buildings that were not exposed to the intervention which renders an energy reduction campaign valuable for long-lasting timeframes. Future research should take into account external factors that could influence energy consumption, such as weather variations, to counter confounding variables.

To specifically investigate the long-term effects of energy behavior interventions, Burns & Savan (2018) conducted a study measuring target behavior frequency for seven months after completion of the intervention. Different types of community-based social marketing techniques were used to stimulate energy-saving behavior among student house residents. Over six months, different modules were implemented that spread tailored information on energy reduction possibilities through stickers, posters, workshops, public saving commitment statements, or a conservation starter's kit with tools that set the first saving impulse. For topical information on the modules, see Table 4.

Throughout the intervention, pro-environmental behaviors increased significantly across all modules compared to baseline measurements, especially for cold-water laundries and water and electricity saving (Burns & Savan, 2018). These behavioral changes persisted for seven months after the intervention ended. No measurements were conducted after this point. Due to the breadth of applied intervention techniques, it is difficult to pinpoint the behavioral changes to any specific measure. For now, it can be concluded that long-term post-intervention changes in energy behavior are possible with a comprehensive intervention that tackles multiple conservation areas at once.

Ornaghi et al. (2018) studied behavioral interventions concerning the self-regulated ventilation of offices and its impact on the buildings' energy reduction. Taking into account that a major part of energy consumption takes place outside of office hours when appliances are forgotten to be turned off (Masoso & Grobler, 2010), Ornaghi et al. (2018) explored windows that were left open during the night. As the intervention, three different emails were sent out every Monday and Friday to encourage window-closing when the heating is turned on, including general information about the need for energy conservation. The first email included just this general information (1), the second email, additionally to the general information, involved feedback on the count of overnight opened windows of the participant's building (2), and the third contained personalized feedback on the number of times one's own window was left open compared to other building users, in addition to the general information (3). Among four different buildings, the emails sent out varied according to the order and the period in which they were sent. For a minimum of seven working days after the intervention, the persistence of the effects was measured.

Across all four studied buildings, the number of left-open windows was reduced by 50% on average (Ornaghi et al., 2018). The energy-conserving behavior remained high after the intervention was stopped. This hints at the potential development of new habits and the need for related information provision to the end-users, resulting in long-term benefits. The best outcome was measured in the building that was exposed to all three emails, one after the other, for the longest amount of time with a reduction of left-open windows of 70%. This indicates that a higher number of interventions employed in successive order results in more positive outcomes for energy reduction in the long run.

- Simultaneous intervention application is more likely to result in significant energy conservation than separate application (e.g., moral appeals & visual prompts).
- Every intervention approach addresses energy behavior in a unique manner which results in unique energy savings (e.g., group-level feedback & peer education).
- Long-term changes in energy behavior are more likely when multiple conservation areas are tackled at once (e.g., different social marketing techniques through posters, workshops, commitment statements).
- In the long run, simultaneous or successive application of multiple saving interventions can lead to higher energy reduction (e.g., emails with diverse information on energy saving behavior).

3.2.2. The longer the intervention, the better

In line with the lesson learned described in the previous sections, it was found that, in addition to the simultaneous application of multiple interventions, **the longer an intervention lasts, the better the outcome for energy conservation and efficiency**. The understanding of this effect is limited of course due to the cost and time restrictions of the reviewed studies, but it is nonetheless insinuated. The reasoning is that over a longer amount of time, it is more likely that pro-environmental habits are created as opposed to intermittent cues (Ornaghi et al., 2018). The more positive outcome becomes apparent **in the short- and the long-run**, when reviewing the previously discussed studies.

Regarding the short-term and long-term perspective, the research by Ornaghi et al. (2018) demonstrates that the longer an intervention lasts, the higher the number of closed windows, thus, the more energy conservation. The first intervention lasting three weeks related to a reduction of left-open windows by 40%, the following intervention of six weeks was associated with a 50% reduction, while the final seven-and-a-half-week lasting intervention related to a reduction of 70% of left-open windows. It seems that, the longer the intervention lasts, the quicker the positive effect increases, almost exponentially. After a minimum of three and a half weeks, the positive effect was maintained from a 7% baseline of left-open windows to a lowered average of 4.9% for the treatment buildings. The maintenance of the previous effects for more than three weeks after the intervention termination implies increased lasting energy reduction the longer the intervention was applied beforehand. **Therefore, the probability of habit creation is positively related to the duration of the intervention**. The positive effects increase the longer an intervention lasts, in the short- and the long-term.

Dixon et al. (2015) exhibit the direct positive effects of an energy decrease of 6.5% after a one year long comparative feedback intervention. As this intervention was the longest lasting of all reviewed literature and the research is one of the few that studied the sustained intervention effects, it can be noted that prolonged energy behavior interventions relate to significant energy conservation immediately and in the long run, until evidenced otherwise. Similarly, Burns & Savan (2018) found significantly increased pro-environmental behaviors after a seven-months long energy behavior intervention, immediately following the intervention. Positive energy reduction changes persisted seven months after the intervention had stopped. Establishing continuous feedback and behavior interventions might be of value to generate sustainable behavior change. However, the feasibility of such an undertaking must be assessed and sustained intervention application over multiple years is yet to be researched.

- The longer the intervention lasts, the stronger the increase of the direct energy reducing effect (e.g., the longer the timeframe over which emails are sent, the less windows are left open).
- The probability of long-term habit creation is positively related to the duration of the intervention (e.g., habit of closing windows when leaving the office).
- Energy reduction campaigns are likely most sucsessfull when applied long-term (e.g., competition among university buildings).

3.2.3. The more concrete and tailored the information provided to the end-user, the better

A third of the reviewed literature evidenced that **energy behavior is more likely to change toward increased conservation when the provided information is concrete and tailored to the building end-users.** This can include knowledge on the specific building and its energy systems or detailed feedback regarding energy behavior that impacts the overall efficiency. Often, **building users are not aware of their impact of their behavior on a building's energy consumption** which is why that information alone can already contribute to lasting behavioral changes (Ornaghi et al., 2018). More detail increases understanding and, with that, conscious adjustments in energy-related activities. The concrete contexts of this lesson learned are elaborated on in the following paragraphs.

Implementing information interventions with group-level feedback or building-specific saving information through peer education, Carrico & Riemer (2011) found that **monthly group-level feedback relates to higher energy reductions** of 7% **than building-specific information** with only 4% savings. The feedback was provided monthly and included positive messages when energy was successfully conserved in the occupant's building, motivating further savings. An energy decrease goal of 15% was set initially as a reference point for the building users. The peer education group only received information on saving opportunities within the building and reinforcements of previously sent general energy conservation information. This suggests that the tailored information provided to the feedback group supplied a higher understanding of the behavioral impact and an increased incentive to change than the more general peer education group. With its low implementation effort and high benefit on energy conservation, the group-level feedback was clearly most impactful. It might lead to even higher savings when implemented more frequently and with more detailed information.

Assessing the effect of different motivational nudges on energy use, Charlier et al. (2021) applied three different interventions through moral appeal emails (1), social comparison on energy use to companies other than their own (2), or visual saving prompts on stickers (3). During a second intervention phase, the moral appeal and the social comparison treatment each included the visual prompts stickers as well. No significant relation was found for any single intervention. The moral-appeal-and-sticker treatment was related to a decrease in electricity and heating use. The social-comparison-and-sticker treatment correlated only with a decrease in electricity use, not heating, and was overall less effective than the formerly mentioned treatment across sample groups. The interventions seemingly have a differing effect on heating vs. electricity use. It is discussed that social comparison and moral appeals in this study increased awareness of energy conservation, whereas the visual prompts served as reminders of daily actions to save energy directly. This led to a coupled positive effect on energy reduction. Corresponding with the overarching lesson learned, the more detail and content provided in the collective nudges, the more effective the intervention. The reasoning, in this case, is that different information serves as different triggers required for behavioral change, like awareness raising or reminding. To further understand the varying impact of social comparison and moral appeals more research should be conducted.

Ornaghi et al. (2018) studied behavioral changes in offices with self-regulated ventilation. They discovered that the emails with feedback on local building performance and those with individual social comparison to other building users were equally effective in enhancing energy conservation, compared to the general information mail. This implies that detailed local information and the pressure of social comparison can stimulate increased adherence to given prompts. In the two successful interventions, local building feedback informed about the user's progress over time, and social comparison presumably triggered a sense of reward or shame when doing better or worse than others. In this case, it is concluded that the more personalized a message is, the better the outcome, especially when occupants are previously not aware of their behavior's effect.

- End-users, especially of non-residential buildings, are often not aware of the impact of their behavior on the building's energy use.
- Tailored information provides building occupants with a higher understanding of their behavioral impact and an increased incentive to change (e.g., social comparison triggering reward or shame)
- Different information triggers different aspects required for behavioral change, like awareness raising or reminders for daily action (e.g., through moral appeals & visual prompts respectively).
- The more personalized the information, the higher the energy conservation, especially when occupants are previously not aware of their behavior's effect (e.g., local feedback informing about progress over time).

3.2.4. Norm changes are not required for energy conservation

While most of the reviewed studies were primarily concerned with behavioral changes, other variables such as norms, perceived importance, or attitudes were measured through pre- and post- intervention surveys as well. The overarching finding of this research was that **a change in norms or attitudes is not required for significant energy reductions to occur**. This is crucial for large-scale interventions in building districts as the diversity and overturn of occupants is high. Norm changes might have to be adapted and readapted to specific target groups of which there are many different ones in the building districts. The input required for norm changes is evidently much higher than that needed for implementing concrete behavioural changes, such as closing a window or a computer, which can occur rather directly and across different types of building users. Further, energy conservation can be increased through smart energy systems that require the input of occupants and their consumption behavior but not necessarily normative changes (Dorokhova et al., 2021; Sanguinetti et al., 2017; Timm & Deal, 2016).

There are two key studies that look at norms, both descriptive (the perception of what other people behave like) and injunctive norms (the sense of a behavior's (dis-) approval by other people) (Nolan et al., 2008). Applying a comparative feedback intervention across competing university buildings, Dixon et al. (2015) measured a significant increase in perceived descriptive norms of energy conservation and in self-reported conservation behaviors in the competing buildings. Behavioral intentions, attitudes, or injunctive norms did not increase significantly throughout the intervention. While this suggests a positive correlation between self-reported behavior and descriptive norms, it does not imply a mediating effect of changing norms which was not measured in this study. Filling this gap, Carrico & Riemer (2011) measured descriptive norms and injunctive norms throughout the intervention research. While both norm types increased, no mediating or interaction effect of the norms on the interventions' effectiveness was found. Norms and conservation behavior showcased a positive correlation, but one did not lead to a more positive outcome than the other. This suggests that norms might increase simultaneously with energy conservation behavior, but a change in the former is no prerequisite for a change in the later.

Accordingly, Burns & Savan (2018) found that, alongside pro-environmental behaviors, general environmental-friendly decision-making rose continuously during and after the intervention. Measured norms and perceived importance of the target behaviors did not change significantly. This outcome clearly contests the presumption that persistent behavioral changes necessitate high attitudes toward the importance of energy-saving and a change in social norms. A positive correlation between the two may be present (Carrico & Riemer, 2011; Dixon et al., 2015) but is not needed for a significant reduction in energy use to occur.

Timm & Deal (2016) examined the impact of direct feedback through energy information dashboards and a 6-week conservation campaign on energy reduction. Every study building was equipped with a display depicting its real-time energy usage and energy education data close to the entrance. The behavior change campaign included the measurements of the energy data, the campaign communication through e.g., regular emails, the creation of an Energy Team responsible for this, and the provision of incentives to strive toward certain energy goals. The measurements of behavioral change occurred mostly through online surveys. Building energy consumption was assessed before and after the intervention.

The building energy analysis demonstrated crucial energy savings in natural gas and in electricity (Timm & Deal, 2016). Yet, within the student and the faculty/ staff sample, no significant changes were found in self-reported energy behavior or attitude. Only the facility managers reported a positive impact of the energy dashboards in finding and solving energy system related issues. This implies that the main impact of this intervention lies with the facility managers, who can control and adapt the settings relating to energy supply. Information that might not have been as visible before, was emphasized through the continuous display of energy data. Energy behavior is not affected directly but rather indirectly by stimulating facility managers to be more proactive in increasing energy efficiency. Changes in attitude were not required in this particular study setting as an increase in energy conservation was caused largely by a better monitoring and visualisation of energy performance information of the buildings, which helped energy managers to take energy-efficiency actions.

- Norms might increase simultaneously with energy conservation behavior, but a change in the former is no prerequisite for a change in the later.
- High attitudes toward the importance of energy-saving and a change in social norms is not necessary for continuous behavioral changes, rather, increased information provision.
- Especially when an increase in energy conservation mainly depends on better monitoring and visualisation of energy performance information, changes in attitude are not required.

3.2.5. Smart energy systems are vital in increasing energy efficiency in buildings

As previously indicated, when employing smart energy systems, the feedback of building users is frequently considered to increase the district’s energy efficiency (Sanguinetti et al., 2017). The regulation of the local HVAC system of a building is often controlled by a facility management team and based on assumptions about seasonal heating or cooling requirements. However, these assumptions can be faulty or lack precision which results in energy usage when it is not needed, thus, leading to energy wastage. To prevent this from happening and make use of energy saving opportunities, information provided by the occupants is made useful through smart energy systems (Dorokhova et al., 2021; Sanguinetti et al., 2017). Beyond faulty assumptions, on-site equipment issues may be discovered through discrepancies between the reported and the set room temperature (Sanguinetti et al., 2017). Exploring these possibilities to reduce energy consumption, a third of the reviewed studies found that **smart energy systems processing occupant feedback on comfort and room usage is positively related to energy efficiency**.

The study of Sanguinetti et al. (2017) aimed to facilitate occupant comfort and increase energy conservation, testing the incorporation of participatory thermal sensing (PTS) at a university campus for almost two years. Through a manual closed-loop system, facility managers could assess feedback given by the building users on their thermal comfort and adjust the HVAC system accordingly. Alongside comfort and energy use improvements, the research intended to motivate building user participation and enhance data interpretation. The newly developed PTS system *TherMOOstat* was accessible through a web portal and a web app in which occupants could give feedback on a 5-point scale whether it was too hot, too cold, or the perfect temperature.

The occupant feedback was cross-referenced with data from the Building Automation System (BAS) (Sanguinetti et al., 2017). This led to the discovery of mechanical issues such as a stuck damper, adjustments to HVAC set points, thorough BAS changes, or the identification of buildings requiring energy retrofits. Seasonal patterns were detected, indicating overheating in the colder seasons and overcooling in the warmer seasons. Based on these results, a new automated control system was proposed to integrate feedback directly into the HVAC programming. Even though quantitative data on the saved energy was not collected, the implications of this research point toward valuable outcomes with increased energy efficiency and occupant comfort at once, through the smart integration of user feedback.

Dorokhova et al. (2021) present findings on the application of an extensive Information and Communication Technology (ICT) platform that aspires to flexibly enhance efficiency in energy storage and use whilst maintaining occupant comfort. The tools used included external inputs like smart meters and sensors, data storage, a gamification platform for occupants, and a set of five applications. Two of these applications were most relevant to this lesson learned. First, there is the occupancy forecast application that identifies energy conservation opportunities for the day ahead. Second, the behavior predictor sends messages to building occupants giving educational or advisory information on energy conservation when consumption is unreasonably high.

The implementation of these applications was successful overall with an office-level occupancy forecasting accuracy of 97.6% despite varying occupancy patterns (Dorokhova et al., 2021). The behavior predictor identified saving opportunities based on the occupancy forecast and verification through the temperature outside. For example, predicted occupancy and data on temperature indicating a warm day would result in an alert to open a window and turn down the air conditioner. The combination of these applications resulted in considerably higher energy efficiency and maintenance of occupant comfort. In this case, feedback was not directly provided by the occupants but through multiple smart energy applications. To further increase efficiency, occupants received feedback from these applications as well to motivate conservation based on their currently assessed energy behavior. This virtuous cycle of continuous feedback evidently leads to a win-win situation with higher energy efficiency and higher occupant comfort at the same time.

With the goal of energy conservation and increased energy literacy of building users, Ramallo-González et al. (2022) tested an individually tailored educational intervention employing an integrated Internet of Things (IoT) platform. With input such as sensor data on the HVAC system, building orientation, environmental data, and user comfort, the system produced real-time personalized energy conservation recommendations in the office. Using gamification strategies, this information was provided to the application users. Energy behavior was measured through user surveys. Energy use data was detected with the installed IoT sensors. During the campaign, the building users were exposed to messages involving advice for energy-saving when consumption was excessive and education on sustainable energy use.

In the survey, 57.14% of the users indicated retained or higher energy-reducing behavior after the campaign (Ramallo-González et al., 2022). Specifically applied to the use of work devices, the average increase in energy-saving activities was 16.11%. Providing information on energy conservation further enhanced energy literacy among end-users. Concerning heating, temperature set points were recommended to be set lower in winter and higher in summer. This confirms the research findings by Sanguinetti et al. (2017) of overheating in the colder seasons and overcooling in the warmer seasons at a university campus. Average energy savings accumulated to 20.9%. Concerning cooling, similar recommendations were given, and the overall savings per year were calculated to be 13.4%. Again, data on user comfort was used to help detect conservation opportunities and inform the occupants thereof. This increases the comfort levels of building users and decreases overall energy usage.

- User feedback on thermal comfort can facilitate the discovery of mechanical issues, efficient adjustments to HVAC set points, and optimal seasonal heating/ cooling patterns.
- Applying smart energy tools such as office-level occupancy forecasting and behavior predicting helps identify conservation opportunities.
- Continuous feedbacking between smart energy tools and building users can increase energy efficiency and occupant comfort from both sides, the HVAC settings and the user behavior.

3.2.6. Gamification is related to increased end-user engagement and energy reduction efforts

When aiming to decrease energy consumption in buildings through behavioral changes, active participation and engagement of the building occupants is crucial. They must understand the impact of their behavior and become motivated to actively change current habits. **To increase energy literacy and motivate significant energy-related behavioral changes, gamification is an effective tool**. In the reviewed studies, gamification is applied through different media and can take the form of an online application, a webpage, or an artificially created competition between two or more parties. The goal of increased energy conservation is oftentimes openly communicated to foster an understanding for the intervention's necessity and the significance of individual changes.

Dixon et al. (2015) gamified their intervention by setting up a year-long energy reduction competition between six university buildings, testing the effect of comparative feedback on energy conservation. Based on self-reported and quantitative energy use data, energy conservation behaviors and energy reduction in the competing buildings increased significantly compared to the non-competing buildings. It is hypothesized that comparative feedback might be especially effective in institutional settings compared to residential settings due to the high peer-to-peer interactions in, for example, universities or companies. The gamified goal of increased energy reduction effectively motivated individuals to change their energy behaviors, potentially with further incentives through the recurring interactions between fellow building users.

Employing the newly developed participatory thermal sensing (PTS) system TherMOOstat, through which building occupants could give feedback on their thermal comfort, Sanguinetti et al. (2017) investigated patterns and reasons for participation in the application. They found that participation generally decreased over time and spiked after targeted promotion efforts and in the fall. This suggests that a PTS system is applicable campus-wide over a longer time with adequate participation rates after regular facilitation. According to a user survey, comfort was the strongest reason to give thermal feedback through the application. Inquiries concerning the temporal impact of the given feedback on building temperature and the workings of the HVAC system and TherMOOstat stood out. This suggests an opportunity for education on energy conservation and related systems. Once introduced, a web app or portal constitutes a low-effort gamification tool that induces user engagement with energy conservation through regular attention-raising and the stimulation of energy literacy-related questions.

Ramallo-González et al. (2022) tested an individually tailored educational Internet of Things (IoT) platform and related gamification strategies. Real-time personalized energy conservation recommendations and educational information were given to the application users. User interactions with the app were recorded. Over half of the participants indicated retained or higher energy-reducing behavior after the campaign. Energy reduction and participation were positively correlated which indicates the link between gamified user engagement and energy conservation. As evidenced in this study, interest is more likely to be maintained when the application is set up creatively and appealing to the user. The number of messages sent should be low enough not to be overwhelming but high enough to keep the user engaged. These insights are of high value to the future implementation of web-based gamification tools to achieve the best possible outcome in terms of user engagement and energy conservation.

- The gamified, communal goal of increased energy reduction can effectively motivate individuals to change their energy behaviors.
- Comparative feedback interventions might be especially effective in institutional settings due to the high peer-to-peer interactions, providing reciprocal conservation incentives.
- Gamified energy reduction tools provide an opportunity for education on energy conservation.
- A web app or portal has a low-cost/high-benfit ratio, feasabile campus-wide with adequate participation rates and reasonable promotion efforts.

3.3. Overcoming organizational and governance challenges

There is a wide range of organisational and governmental challenges that may relate to social, psychological, political or economic aspects, as well as other factors (Köhler et al., 2024). This section summarises the best practices to address these challenges that we found most helpful for the Urban Living Labs in PED Stepwise based on the literature review and the analysis of energy transition projects.

The selection focuses on studies and projects that aim for a just and participatory energy transition. This has the advantage of both leading to better results and increasing the trust of stakeholders (Ross & Day, 2022). As Ryder et al. (2023) emphasize, resistance to heat/energy transition projects often arises in response to top-down projects that allow little room for participation. However, a high level of acceptance is important, because a successful heat/energy transition process also has an impact on the long-term use and maintenance of the buildings (Morgan et al., 2024). This is particularly important in housing contexts, as it is about the residents' homes and their well-being, which also involves emotional and identity issues. Heat/energy transition measures most often involve disruptions to residents' homes and their social practices and routines in using technology, but also in their everyday lives, as Morgan et al. (2024) point out. To counter fears and avoid resistance, a sensitive and respectful participation process is therefore essential for successful project implementation and thus for the goal of a heat/energy transition. In the PED-ID project, such participatory approaches include building trust through a Letter of Intent among stakeholders and tailoring communication strategies to address specific concerns, which have proven effective in engaging diverse groups (PED-ID Final Report, 2022).

It is important to emphasize that this section is a collection of insights from specific contexts. These can hardly be universally applied to other contexts but must be adapted to the specific framework conditions of each case. This applies in particular to the three Urban Living Labs of PED Stepwise, which are characterized by very different conditions and objectives. Nevertheless, we believe that such a collection is useful as it can serve as a starting point for each case. For instance, in the context of KfW's Energetische Stadtsanierung program, early stakeholder involvement and the use of targeted subsidies have facilitated successful neighborhood-specific redevelopment, supporting climate-friendly mobility and energy efficiency (BBSR 25/2017, KfW Program 432 Guide). Additionally, the continuous support and advisory services provided by redevelopment management have enhanced stakeholder understanding and commitment to sustainable urban practices (Energetische Stadtsanierung, 2017).

To present our findings on organizational and governance challenges in a structured way, we refer to the SET-Plan (Strategic Energy Transition), a European initiative that aims to establish 100 Positive Energy Districts (PEDs) by 2025. The SET-Plan identifies three social challenges, which we use as a structuring principle in this section: stakeholder interaction, participation and capacity building. In the following, we will discuss the individual insights regarding these three main points and briefly explain the conclusions that can be drawn from them with reference to specific studies and projects.

3.3.1. Stakeholder Interaction

Stakeholder interaction refers to the structured engagement and collaboration among various parties, including industry representatives, research organizations, governmental bodies, and civil society. This collaborative approach ensures that diverse perspectives are considered in the planning and implementation of energy technologies, facilitating consensus-building and the alignment of objectives across sectors.

Integrate different organisational and governmental levels

Baer et al. (2021) emphasize the importance of vertical integration of organizational and governmental levels, e.g., municipal institutions and federal agencies. Effective collaboration between local, regional, and national authorities is essential for the success of energy initiatives at the local level. For instance, alignment of policies and regulations ensures that local governments do not face legal or bureaucratic obstacles due to conflicting rules at different levels. Additionally, efficient resource allocation with proper coordination can ensure resources are distributed effectively. Furthermore, clarifying roles and responsibilities among stakeholders, helps prevent confusion, delays, and duplicated efforts.

Co-create to improve citizens engagement

Co-creation is a collaborative process where multiple stakeholders, such as customers, employees, partners, or communities, work together to actively create value, products, services, or experiences. Unlike traditional methods where a company designs and delivers a product to a passive audience, co-creation involves direct participation and input from all parties involved, leading to innovative solutions and deeper engagement. As Sherry-Brennan et al. (2022) emphasise, there is no one-size-fits-all best practice for co-creation, as each local context is unique and a wide range of methods can be applied. However, there are some important aspects and approaches that the reviewed literature and projects highlight as helpful and effective in co-creation for sustainable heat and energy. First, co-creation should actively involve citizens and local communities in designing, planning and implementing transitions towards sustainable heat (see next section on participation). It is also important that the roles and responsibilities of the various partners are clear and that these are also fully documented in order to make agreements transparent, as Lucas et al. (2024) emphasise. Also, Lucas et al. (2024) point out the importance of a joint process with the partners to define the goals and approaches of stakeholder engagement. They emphasise that it is important to have a jointly developed vision for the project that also refers to higher-level energy goals and priorities. Second, This can also be an iterative process of adjusting goals and outcomes, for which there should be opportunities for feedback and adaptation (Lucas et al., 2024). Also, Itten et al. (2021) and Sherry-Brennan et al. (2022) point out that the co-creation process is often iterative and non-linear, so it is important to remain flexible and adapt to new circumstances and insights. An iterative, reflexive approach is recommended that promotes interaction between citizens and stakeholders and enables a rapid transition to sustainable solutions (Itten et al., 2021; Sherry-Brennan et al., 2022). Third, it is important to recognise and try to overcome existing inequalities in power, knowledge and resources between citizens, municipalities and energy companies, as Sherry-Brennan et al. (2022) point out. Co-creation should provide opportunities for self-organisation to minimise these inequalities. As Itten et al. (2021) conclude, it is important that co-creation is not seen as a panacea, but as one of many possibilities for shaping a transition to sustainable heating systems.

It requires careful planning, implementation and evaluation to ensure that the needs and interests of all stakeholders are taken into account (Itten et al., 2021).

The importance of information sharing and trusted intermediaries

As Morgan et al. (2024) emphasize, a lack of information, both between the partners involved and within individual organizations, is often a significant barrier to progress. Partners, therefore, need sufficient and timely access to comprehensive information (including details on the technologies, systems installed, and their integration). This access to information should be given great consideration during project planning and execution. The benefits of similar approaches have been evident in the PED-ID project where continuous feedback mechanisms and the role of a trusted intermediary, or 'process leader', have been instrumental in mediating stakeholder interests and harmonizing project objectives (PED-ID Stakeholder Process, 2022). The role of the trusted intermediary also aligns with the practices observed in program of a German development bank, where clear, transparent information and collaborative models foster long-term partnerships and community engagement in energy projects (BBSR – Bundesinstitut für Bau-, 2022).

- Coordination between different organizational and governmental levels, such as municipal institutions and federal agencies, is essential for effective collaboration, with clearly defined roles and responsibilities to ensure transparency and accountability.
- Effective co-creation requires active citizen and community participation, clear roles and responsibilities, and a joint vision aligned with broader energy goals. The process should be flexible, iterative, and reflexive, allowing continuous feedback and adaptation while also addressing inequalities in power, knowledge, and resources between stakeholders.
- Timely access to comprehensive and transparent information to all key stakeholders is crucial for project success. Trusted intermediaries or 'process leaders' can help facilitate communication, mediate stakeholder interests, and align project objectives to ensure effective collaboration and decision-making.

3.3.2. Participation

Participation refers to the active involvement and collaboration of a diverse range of stakeholders.

Encourage broad citizens participation to increase trust and manage expectations

In general, many studies point to the importance of participation to support the energy transition and achieve acceptance of new energy measures (Bouw et al., 2023; Haug et al., 2020; Köhler et al., 2024; Lucas et al., 2024), including in all areas of participation, whether financial/economic, technical or social (Teladia & van der Windt, 2024). Sovacool (2014) points out three main advantages of participation: (1) democratization, as all citizens can participate in decision-making, (2) people have a greater awareness of ethical aspects, such as inequality, which are thus given more consideration, and (3) greater acceptance of potential new energy measures.

Morgan et al. (2024) add that **participation can prevent misunderstandings and help manage expectations**. The authors argue that this is important because trust is a key aspect in the context of home modifications, and otherwise lack of trust can lead to negative community stories which can quickly spread. As also Brown et al. (2014) found in the context of residential building renovations, trust is an important aspect for the success of the project and can represent a critical barrier. Ryder et al. (2023) add as an advantage of participation processes that projects can usually be completed more quickly. In addition, a strong involvement in the process can increase general energy literacy and understanding of the climate crisis and sustainability issues, which can lead to cultural changes in relation to the climate crisis and the necessary measures (Morgan et al., 2024).

In the PED-ID project, successful strategies for maintaining long-term engagement have included the **implementation of continuous feedback mechanisms** and the **use of a neutral 'process leader**' to facilitate ongoing dialogue between stakeholders (PED-ID Stakeholder Process, 2022). When working with communities, these process leads should generally lead the process and community agency should be prioritised, as Ross & Day (2022) point out. In the KfW's Energetische Stadtsanierung, successful participation strategies have included organizing local events and workshops that foster a direct dialogue between stakeholders, enhancing their engagement and commitment to the project objectives (Energetische Stadtsanierung, 2017). It is also helpful not to focus on specific solutions, but on shared goals and objectives, as this allows for more creativity in co-development (Ross & Day, 2022).

In this context, it is particularly important to have a representative group of stakeholders addressed in the participation process and to **reach out to groups that are less likely to engage**. As Bouw et al. (2023) claim, this is the only way to achieve broad acceptance of the energy measures. Accordingly, it is also important to recognise the diversity of groups involved and to adapt the formats of participation to the needs of the addressed groups. With multilingual stakeholders, this may also mean that translators should be consulted (Lucas et al., 2024). Project teams should also seek diversity to better match the diversity of the stakeholders (Ross & Day, 2022). In addition, the opportunities for participation should be broad and flexible to enable people who would otherwise not be able to participate, for example due to family commitments, accessibility needs, travel restrictions or other limitations (Lucas et al., 2024). For example, in a study by Morgan et al. (2024) there was evidence that older adults and those in financially precarious circumstances were excluded from the programme or not consulted on installing the technologies.

Providing broad and flexible opportunities for participation may also mean to meet stakeholders where they are – not just figuratively but also spatially (Ross & Day, 2022). In general, meeting times and locations should prioritize low-power stakeholders to minimize power differentials and be as inclusive as possible (Ross & Day, 2022). This could also mean compensating precarious stakeholders for their time (Ross & Day, 2022). Working with local facilitators and organisations may also help (Ross & Day, 2022). Similarly, Teladia & van der Windt (2024) emphasise that working with existing neighbourhood organisations provided very valuable support and networks. Bouw et al. (2023) also emphasise that in meetings, an open atmosphere, without the immediate pressure to make a decision, is important for participants to express their opinions. Moreover, as Köhler et al. (2024) indicate, **participation needs time and resources**.

Another important topic regarding the representativeness of decisions is digital exclusion. As Morgan et al. (2024) point out, this can lead to certain households, especially those with older residents, not participating in decision-making. Furthermore, some technologies require Wi-Fi or a smartphone, which makes it difficult for some households to use these technologies. Accordingly, teaching digital skills is essential. At the same time, **however, participation does not automatically guarantee acceptance**, as Haug et al. (2020) emphasise.

Teladia & van der Windt (2024) stress that the participatory environment is critical to the extent and manner in which people participate, thus how characteristics of the local neighbourhood encourage participation. In their study of five Dutch community heating initiatives they use the term 'enabling participatory environment' to refer to various characteristics of the affected groups and areas, such as socio-economic characteristics (e.g. income level, education), knowledge about sustainability, the existence of other energy projects in the local area, the availability of sustainable energy technology or the presence of governmental and non-governmental organisations in the area.

Enable participation from the beginning

Several studies and reports emphasise that involving various interest groups from the outset is crucial to the success of any project (Lucas et al., 2024; Morgan et al., 2024). For instance, Lucas et al. (2024) underline the advantage of early involvement in facilitating the implementation of efficient and feasible projects, **ensuring that stakeholders are well-informed about the costs, benefits, and potential drawbacks from the beginning**. In the KfW's Energetische Stadtsanierung program, this early engagement is structured around providing stakeholders with comprehensive role definitions and expectations which significantly enhance their ability to contribute meaningfully from the onset (KfW Program 432 Guide). This approach fosters transparency and allows for more realistic expectations. Accordingly, stakeholders should not merely be asked to approve pre-determined solutions; instead, they should actively participate in the development of solutions from the very start, as Ross & Day (2022) emphasize. However, it is **equally important to define clearly from the outset the extent to which stakeholder input can influence the project's decisions**. Without this clarity, there is a risk of creating unrealistic expectations, which, if unmet, can erode stakeholder trust and undermine the overall success of the initiative (Ross & Day, 2022).

Moving beyond tokenism and achieving genuine community engagement

It is crucial for successful participation processes in energy projects not to be merely instrumentally driven and aimed at social acceptance (Ryder et al. (2023). This can jeopardize the entire project, as the trust between the groups involved is at risk and the local community may reject the project. The problem arises when the engagement process does not provide for real stakeholder involvement, but merely meets the minimum requirements for engagement in a one-way communication. As Ryder et al. (2023) note, in these cases residents may perceive the engagement process as a mere 'box-ticking exercise. This may also sometimes occur when the developers offer financial incentives to the affected people, which may be perceived as 'bribes', while the residents' substantive concerns about the project are ignored. What is called engagement in these cases is actually non-participation, as Ryder et al. (2023) argue.

To avoid this tokenism, Ryder et al. (2023) formulate an '**ethics of care' in the engagement process.** They list the following: valuing the knowledge of the residents; greater agency for the residents in decisions about the local area; the involvement of local workers and individuals; offering the residents opportunities for ownership in the project; the general 'localisation' of the project through greater attention to local particularities that are important to the community. Generally speaking, it is about not only focusing on outcome and the engagement process as a means to an end, but also on the process itself and the value of fairness.

Enable transition from passive consumers to active prosumers

Various studies emphasize that not only participation in decisions but also the transition from passive consumers to active prosumers is crucial for the successful implementation of PEDs. For example, Baer et al. (2021) examine three PED projects in Norway – ZEN, +CityxChange and syn.ikia – and argue, that PEDs rely on the active participation of citizens in energy production and management. By becoming prosumers, citizens can **directly benefit from the advantages of local energy production**, such as lower energy costs and greater energy independence. In addition, by actively participating in their energy supply, citizens are empowered and take responsibility for their energy future. Furthermore, the acceptance of energy measures is higher when citizens themselves are involved in their production. Haug et al. (2020) also identify this as a reason why there are fewer conflicts and a greater willingness to embrace the energy transition in housing cooperatives, where residents have partial ownership, than among other stakeholders. Ownership is generally seen as an important aspect in advancing energy projects, or conversely, a lack of ownership can lead to a lower willingness to participate, as emphasised by Teladia & van der Windt (2024).

This may also be the reason why **participation seems to be most likely in projects including citizens cooperatives,** as they are accustomed to participation, as Haug et al. (2020) argue. As they emphasize, what is most important in this case, however, is a relationship of trust between the residents and the board of the cooperative. Similarly, Teladia & van der Windt (2024) emphasise that cooperative structures are helpful because they provide a clear path for participation and decision-making. The local community can play a significant role in the decision-making process for example in the Annual General Meeting or in working groups.

Analysis to understand context and priorities is essential for participation processes

Lucas et al. (2024) emphasise that the knowledge and understanding of the specific stakeholders is crucial to the success of the project. This includes, in particular, **understanding the priorities and objectives of the various partners**. Ross & Day (2022), coming from the field of community engagement, also emphasise that comprehensive knowledge of the community context is important and is a prerequisite for asking important questions, recognising **differences and specific needs,** and ultimately generating context-specific options. As Morgan et al. (2024) point out, communication should therefore be tailored and adapted to the specific target group and, for example, be oriented towards laypersons and take into account the low level of education among the poorer sections of the population.

The PED-ID project further supports this tailored approach by implementing adaptive communication strategies that are responsive to real-time feedback, ensuring that stakeholder interactions are both relevant and impactful (PED-ID Final Report, 2022). Bouw et al. (2023) highlight the importance of knowledge about the sociocultural characteristics of the neighbourhood in order to develop suitable solutions and measures. They present the example of a 'social profile' created through a survey and show how this knowledge can be used in the practical implementation of projects. Schleer et al. (2024) have taken a promising approach in this regard, in that they have investigated the different attitudes of various groups towards the climate crisis and socio-ecological transformation. Based on Sinus-Milieus, they have identified the barriers that exist for different milieus and the communication strategies and points of contact that can be drawn from them. For example, when communicating with anti-technological and anti-scientific milieus in precarious living conditions, which are (strongly) distanced from or even opposed to change, there is little point in using idealistic arguments and communication strategies, while cost savings and costs arguments are more promising to gain their support.

In line with this, the KfW's Energetische Stadtsanierung program emphasizes the tailored engagement of different stakeholder groups through specialized educational sessions that address unique community concerns and enhance collaborative problem-solving (KfW Program 432 Guide). As Ross & Day (2022)emphasise, recognizing sociocultural differences may also mean, that one should proceed in a language-sensitive manner when talking about the energy transition, for example, by using accessible language or defining frequently used terminology. In any case, **communication should be specific to the groups one is communicating with and to what they consider important** (Ross & Day, 2022). **Taking into account the exact socio-cultural characteristics of the addressed groups** is also helpful because existing extensive knowledge about sustainability and climate crisis issues on the part of the group is beneficial for the advancement of the project, as Teladia & van der Windt (2024) emphasise. The level of education of the people concerned is therefore crucial for the likelihood of successful project.

However, as Lucas et al. (2024) emphasise, it is also important to consider that individual **stakeholder groups themselves can be complex and diverse and do not necessarily have the same preferences.** Taking these differences into account leads to a more inclusive and robust process.

Analysing the individual stakeholder groups often also means realising that the energy transition is not a priority for all stakeholders, but that they have very different goals and priorities and are confronted with very different challenges (Lucas et al., 2024). Similarly, Schleer et al. (2024) also emphasise this by pointing out that precarious milieus in particular perceive the climate crisis as a secondary problem and that unemployment or health problems, for example, are more important. Carbon reduction therefore plays little or no role in everyday life. Aiming for net-zero right from the start may therefore be a challenging approach in such contexts, as Lucas et al. (2024) emphasize.

Use a combination of tools and communication formats to enhance stakeholder engagement

This point concerns not only participation but also, fundamentally, stakeholder interaction and capacity building. As Bouw et al. (2023) highlight, **achieving robust, reliable results and well-informed decisions requires the use of diverse tools to convey varied information and effectively engage different groups.** Without such variety, there is a risk of one-sidedness that could undermine the inclusiveness and validity of the process. Morgan et al. (2024) further emphasize the **importance of delivering knowledge in multiple formats and at various stages** throughout the program. This ensures that information resonates with different audiences and accommodates varying learning styles.

The delivery of information should incorporate a blend of media, including written materials (e.g., reports, brochures), verbal presentations (e.g., speeches, discussions), and visual aids (e.g., infographics, videos, or animations). Participation and communication channels can also be tailored to meet specific needs and preferences. Examples include digital platforms such as websites and newsletters for widespread outreach, alongside more intimate settings such as community meetings, working groups, or focus groups to foster direct interaction. Additionally, house visits, walking tours, and the involvement of street ambassadors offer personalized approaches that can build trust and rapport. By diversifying communication methods and channels, programs can more effectively ensure that all stakeholders are informed, engaged, and empowered to participate meaningfully.

Adress infrastructural disruptions through transparent communication

As Morgan et al. (2024) note, the disruption caused by construction work as part of heat transition processes poses a significant barrier for residents, often discouraging others from joining the process. **Clear and transparent communication that accurately addresses and identifies these infrastructural disruptions**—such as their expected duration and extent—is therefore critical for ensuring a successful process. One effective strategy is to work with empty buildings wherever feasible, allowing technologies and procedures to be demonstrated without causing inconvenience to residents. Additionally, showcasing similar, successfully completed projects and buildings as models can help illustrate the extent of the disruption and the technologies employed. Providing real-life examples can foster trust and understanding, as households are often more willing to participate if they can observe others who have successfully navigated the process. Open forums, testimonials from participants, or organized tours of completed projects can further build confidence among hesitant residents.

- Participation in financial, technical, and social aspects is essential. It democratizes decision-making, raises ethical awareness, and enhances project acceptance. Trust is crucial for success, and engagement strategies like continuous feedback and neutral facilitators help maintain long-term involvement.
- Efforts should be made to involve diverse stakeholder groups, particularly those who are often excluded, such as older adults or financially disadvantaged individuals. Flexible participation options, language support, and fair compensation can improve inclusivity.
- Stakeholders should be engaged from the beginning, not just asked to approve pre-determined solutions. Clear expectations help prevent misunderstandings and build trust.
- Participation should not be a mere formality. Instead, an "ethics of care" approach should value local knowledge, involve residents in decision-making, and avoid financial incentives that might be perceived as bribes.
- Active citizen participation in energy production increases acceptance and sustainability. Ownership and cooperative structures foster engagement.
- Understanding stakeholder priorities is essential. Effective communication should be tailored to different groups, considering education levels, cultural differences, and digital accessibility.
- A combination of formats (e.g., meetings, digital tools, community events) ensures broad and effective participation.
- Clear communication about construction impacts during project implementation and showcasing successful projects can ease concerns and encourage participation.

3.3.3. Capacity Building

Building stakeholder capacity through education and engagement

Several studies and projects, such as Ross & Day (2022) or Baer et al. (2021), emphasize the importance of educational activities to build the capacity of stakeholders in order to advance energy transition projects. This can include basic information on climate change and the technologies used, as well as specific instructions on how to use new devices and what end users can expect, benefits, challenges and downsides of specific solutions. Most people are not familiar with energy technologies and their consequences in terms of costs, maintenance, living quality, etc. However, in order for them to be able to make decisions, it is essential that they are provided with basic knowledge about these topics. In the PED-ID project, educational activities have been integrated into participation strategies through co-creation workshops, which enable stakeholders to understand and influence the planning and implementation processes directly (PED-ID Final Report, 2022).

Bouw et al. (2023) present the example of Information-Choice Questionnaires (ICQs), designed to provide respondents with the information necessary to make informed choices, thus combining educational and knowledge objectives. However, Bouw et al. (2023) also point out that the formation of educated opinions is complex and information provision alone is not sufficient. Uncertainty about energy prices, technology availability, legislation and regulation also complicates the decision-making process.

Another example is the KfW program which uses showcasing previous successful projects as a method to illustrate potential benefits and practical implementations, helping stakeholders visualize the possible outcomes and fostering a better understanding of the processes involved in previous gained experiences (KfW Program 432 Guide). Continuous feedback and ongoing educational support are also emphasized in the KfW's Energetische Stadtsanierung program, where the long-term engagement and learning of stakeholders are considered crucial for maintaining and advancing sustainable practices (KfW Program 432 Guide). Bouw et al. (2023) also emphasise that it is **important to repeat information several times on different occasions**, as not all participants can participate in all activities. Moreover, as Morgan et al. (2024) emphasize, different **citizens sometimes have different information needs, and stakeholder engagement should also address this.**

As Morgan et al. (2024) point out, a lack of information and weak communication are still a problem even after the construction work has been completed. This particularly affects the efficient use of the technologies employed, as misuse can lead to higher costs and jeopardize the goal of low carbon emissions. As mentioned earlier in the last section, the transfer of digital knowledge is essential for participatory decision-making processes that involve the use of new digital technologies and especially when these include older households. Similarly, the PED-ID project utilizes a variety of educational formats, including digital media and face-to-face interactions, to ensure that all stakeholders, regardless of their technological proficiency, can fully engage with and benefit from the project initiatives (PED-ID Final Report, 2022).

Build agency

Several studies and projects have shown that it is important to empower users to continue energy solutions and measures, such as the correct use of a particular heating system, on their own after the project is completed. As Ross & Day (2022) emphasise, this can take various forms, such as teaching users how to use certain tools or technologies, which in turn enables them to instruct other users themselves. Having responsible individuals or point persons to continue the measures and solutions after the project has ended also increases the likelihood that the agreed plan will be adhered to (Ross & Day, 2022).

As Morgan et al. (2024) point out, another way to increase the agency of users is to design the technologies in such a way that they correspond to the users' familiar material culture. This can be achieved, for example, by designing digital interfaces that are similar to analogue components.

- Stakeholders need basic knowledge about climate change and energy technologies to make informed decisions. Ongoing education through workshops, digital media, and real-life examples ensures effective participation. Addressing different information needs, particularly for older adults, helps avoid misuse of technologies.
- Empowering users to maintain solutions after the project ends is crucial. This includes teaching them how to use technologies and designing user-friendly interfaces. Empowered users are more likely to continue following sustainability plans.

4. Application of best practices to the living labs

Table 5 provides a summary of key lessons from the review of the three topics relevant for the PED StepWise project. In particular, the summary pays attention to how the insights gained from these best practices can inform the design of our stakeholder engagement strategy (WP3), guide its practical implementation and the techno-economic analysis of the living lab (WP4), and enhance our communication efforts with end-users and stakeholders (WP6). By analyzing these examples, we aim to identify actionable strategies that can strengthen collaboration, improve outreach, and support the successful realization of PED StepWise objectives.

Table 5 Overview of key lessons learned of the three topics reviewed and the identified links to potential activities in three working packages of PED StepWise

	Main lessons learned	Links to potential WP3 activities (design of engagement strategy with stakeholders)	Links to potential WP4 activities (techno-economic analysis and implementation of engagement strategy)	Links to potential WP6 activities (communication strategy)
Energy sharing	• Energy sharing is heavily influenced by national regulations. National legal structures can enable or hinder energy sharing, with Austria making progress while Sweden and the Netherlands face still challenges. • ECs take different forms, such as cooperatives or private businesses, requiring strong governance for financial sustainability and fair profit-sharing. • Financial viability depends on incentives, energy-sharing models, and technologies like blockchain and battery storage, with some models still unproven.	• Identifying key stakeholders in the living labs (local governments, DSOs, prosumers, businesses) and their potential roles in ECs working towards energy sharing. • Analyzing further regulatory frameworks to assess stakeholder involvement (see section 3.1.1). • Examining social acceptance challenges and strategies for community engagement in energy sharing. • Exploring governance models to ensure inclusive decision-making in ECs working towards energy sharing.	• Evaluating financial incentives, grid fee reductions, and feed-in premiums in different national frameworks. • Assessing economic benefits of ECs and energy sharing models, including energy cost savings and investment models. • Analyzing market models such as peer-to-peer trading, internal pricing mechanisms, and blockchain-based transactions. • Investigating profitability, cost-benefit trade-offs, and scalability of ECs.	• Raising public awareness about the benefits and challenges of energy sharing. • Showcasing best practices and case studies and promoting success stories of pilot projects from Austria (e.g. eFriends, OurPower, Grätzl Energie), Sweden (e.g. Tamarinden, ElectriCITY, SIMRIS), and the Netherlands (e.g. Republica, Aardhuizen). • Developing knowledge-sharing platforms and policy recommendations for stakeholders.
Reduce energy demand of end-users	• The more diverse the interventions, the better in the short-and long-term. • The longer the interventions, the better. • The more concrete the information provided, the better. • Norm changes are not required for energy conservation.	• Assess energy literacy of building users in the living labs. • Create awareness for the impact of individual energy behavior within total building energy use. • Examine current user engagement strategies within the living labs • Create a feedback structure between building occupants and facility managers.	• Identify opportunities for energy efficiencies gains from energy-behavioral changes • Evaluate existing tools to provide building users with energy information. • Assess the practical and financial feasibility of the long-term implementation of behavioral change interventions.	• Increase communication of buildings' energy use data and the relevance of individual behavior. • Disseminate information on current best practices and encourage new ideas, adapted to specific buildings • Promote engagement possibilities for energy conservation among end-users

	• Occupant feedback is vital in increasing energy efficiency. • Gamification is related to increased occupant engagement.	• Evaluate current thermal occupant comfort and its relation to building energy efficiency.	• Explore the costs and benefits of implementing smart energy tools to enable feedback cycles between building users and energy systems/ facility managers.	• Ensure interdisciplinarity when working to implement persisting energy behavioral changes. • Communicate energy conservation must be promoted as a communal goal, but with individual responsibilities.
Overcoming organizational and governance challenges	• Effective energy projects require coordinated efforts across organizational levels, clear roles, transparent information, and trusted intermediaries to ensure successful collaboration and decision-making. • Successful energy projects require inclusive participation from diverse stakeholders, clear communication, active citizen engagement, and tailored strategies to build trust, address concerns, and foster long-term involvement. • Effective participation in energy projects requires ongoing education on climate change and technologies, while empowering users with knowledge and user-friendly tools to maintain solutions and engagement post-project.	• Ensure effective collaboration across organizational levels with transparency and trusted intermediaries. • Involve diverse stakeholders through tailored strategies to build trust and address concerns, ensuring long-term involvement. • Provide continuous learning on climate change and energy technologies to support informed decision-making. • Equip stakeholders with knowledge and user-friendly tools to maintain solutions after the project ends, ensuring sustainability.		• Adapt communication to meet the diverse needs of stakeholders, considering factors like education levels, cultural differences, and technological access. • Use a mix of communication formats (e.g., meetings, digital tools, community events) to reach stakeholders with different preferences and abilities. • Ensure that information is accessible to all, including marginalized groups (e.g., older adults or financially disadvantaged individuals), to prevent exclusion. • Showcase successful projects and potential benefits to encourage participation and alleviate concerns about project impacts. • Use trusted intermediaries or facilitators to help mediate stakeholder interests, ensuring a balanced and fair decision-making process.

5. Conclusion

This Best Practices Report, developed within Work Package 2 of the PED StepWise project, aims to identify effective strategies and innovative solutions for overcoming key challenges in the decarbonization of existing buildings at the district level. The goal is to leverage lessons learned to develop actionable strategies that can inform and support PED implementation and CO_2 reduction efforts in the living labs of Vienna, Malmö, and Utrecht.

Three topics were identified for investigation in the Best Practices review. The topics aligned with existing challenges and interesting options to investigate in the three living labs. The three topics investigated in the report are: Energy-sharing, reduce energy through behavioral changes, and overcoming organizational and governance challenges.

The first topic reviewed focused on energy sharing. Energy sharing, a collaborative approach within local communities or grids, plays an important role in PEDs and energy communities. The report gives insight into three key areas: Policy and Regulatory Frameworks, Governance and Operational Models, and Innovative Technologies to allow energy sharing.

The review of literature and studies around energy sharing highlights that the development and implementation of energy-sharing practices across various countries varies per country, with some countries making progress while others facing still many challenges. Austria stands out as a leader with its well-developed regulations and supportive infrastructure, despite administrative complexities. Sweden and the Netherlands are in the early stages, with pilot projects and new laws being developed to overcome legal and practical barriers. Innovative models and technologies, such as blockchain-based trading systems and community battery storage, are being explored, and the first pilots in various countries are being implemented to optimize local energy use, decrease energy costs, and ensure fair distribution within energy communities. Government funding and decentralized models further support the adoption and implementation of these practices, addressing issues like high costs and lack of clear roles of the parties involved in energy-sharing projects. As these countries continue to refine their approaches, the potential for scalable and efficient energy-sharing systems becomes increasingly promising.

The best practice review brings a few key recommendations for WP3 in PED StepWise. For example, to analyze further national regulations in each living lab affecting energy sharing, identifying enabling and hindering factors. Another recommendation is to clarify stakeholder roles (local governments, DSOs, prosumers, businesses) to enhance collaboration and ensure strong governance models for financially sustainable energy communities (ECs). For WP4, an opportunity is to assess financial incentives, grid fee reductions, and feed-in premiums to improve the viability of energy-sharing schemes. Moreover, we recommend evaluating market models like peer-to-peer trading, internal pricing, and blockchain transactions to explore cost-benefit trade-offs, profitability, and scalability. For WP6, there is an opportunity to raise public awareness by showcasing best practices from Austria, Sweden, and the Netherlands. Developing knowledge-sharing platforms and policy recommendations can also promote the adoption of energy sharing and drive regulatory improvements.

The second topic reviewed in the report addressed behavioral interventions to increase energy conservation in non-residential buildings. Nine papers were examined in-depth. Across this literature, six main lessons learned were discovered, each supported by at least three of the nine studies and with relevant sub-findings that can be applied to various types of building districts – universities, companies, or other research institutes.

Overarching, it was strongly supported that behavioral change interventions applied to the individual or groups of building occupants are significantly positively related to measurable energy reduction. With different approaches, energy behavior can be tackled from various angles that each lead to unique contributions to a building's energy conservation. This becomes prevalent in the finding that more diverse interventions relate to higher and persisting energy savings. Similar results are found for interventions with a longer implementation duration. For building users to be most responsive to energy reduction incentives, detailed and tailored information is most effective. Changes in personal norms are not necessary for behavioral changes to occur. Going full circle, end-users should not only receive feedback but also provide feedback regarding their comfort levels in the room to increase energy efficiency from the side of the facility management. Gamification of information and feedback platforms here can increase end-user engagement. Creating these reciprocal feedback structures and implementing energy reduction as a communal goal with the leverage of the individual is, thus, vital to reaching persistent positive change.

Given the insights gained in the review of the topic energy behavior, key recommendations for WP3 of the PED StepWise project include raising awareness of the impact of individual energy behavior in CO2 reductions. It is also important to create feedback structures between building users and facility managers and further investigate the association between building user comfort and energy efficiency. Strategies to increase user engagement with energy conservation and improve end-users' existing energy literacy must be examined. Insights relevant to WP4 of the project entail the need for an evaluation of existing energy information provision tools, the feasibility of long-term behavioral change interventions, and a cost-benefit analysis of smart energy systems. For WP6, communication of information on energy use, behavioral impact, and current best practices must be facilitated, and new ideas for different types of buildings should be stimulated. Local energy conservation must be promoted as a communal goal that requires interdisciplinarity and individual responsibility.

The review of best practices of the third topic discussed key challenges related to the organization and governance of energy transition projects. It highlights the importance of stakeholder engagement, participatory decision-making, and capacity building to ensure the success and acceptance of energy initiatives. Resistance to such projects often arises from top-down approaches that limit public involvement, which is why fostering trust and inclusivity through early and continuous engagement is crucial.

Best practices emphasize the role of co-creation, ensuring that citizens actively participate in the design and implementation of sustainable energy solutions. Flexible and iterative engagement processes, along with inclusive formats, help address inequalities in power, knowledge, and resources. Participation should be meaningful rather than tokenistic, avoiding mere compliance with formal requirements. Additionally, capacity-building efforts, such as education on climate change and new technologies, play a vital role in empowering engagement in communities. Encouraging the transition from passive consumers to active "prosumers" enhances acceptance and ownership of energy projects. To sustain long-term engagement, projects must integrate various communication tools, accommodate diverse needs, and address socio-economic differences. By adopting these best practices, energy transition initiatives can foster broader acceptance, leading to more effective and sustainable outcomes.

Given the findings above regarding best practices around organization and participation, a few key recommendations for WP3 and WP6 of the PED StepWise project are highlighted: To ensure inclusive participation, it is important to adapt communication to different stakeholder needs, taking into account education levels, cultural differences, and unequal access to technology. A combination of communication formats, such as in-person meetings, digital tools, and community events, should be used to reach stakeholders effectively. Special attention must be given to marginalized groups, including, for example, older adults and financially disadvantaged individuals, to prevent exclusion. Showcasing successful projects can help alleviate concerns and encourage participation, while trusted intermediaries can play a critical role in mediating interests and ensuring fair decision-making.

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7.PED Stepwise Consortium

Austria	Sweden	Netherlands
e7 Energy Innovation Engineering realitylab Arteria Technologies gartenheim	Malmö stad Kungl Tekniska Högskolan (Vetenskap och Konst) RI. SE white M·F·F Malmö FF e·on	Hogeschool Utrecht Utrecht University