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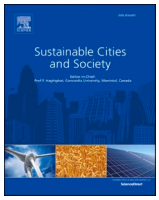



Unraveling the implementation processes of PEDs: Lesson learned from multiple urban contexts

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ABSTRACT

The implementation of Positive Energy Districts (PEDs) is recognized as a promising approach to achieving energy efficiency and reducing the negative environmental impact of climate change through the surplus of local renewable energy generation. However, several barriers to the implementation of PEDs, coupled with the lack of a joint definition and clarity surrounding PEDs, need to be addressed. These barriers include governance, incentives, social, process, market, technology, and context challenges, requiring a profound understanding of the priorities, ambitions, strategies, contextual conditions, administrative conditions, policies, economic and technical resources, and existing solutions of cities.

This study explores the creation and implementation of PEDs, seeking to uncover the potential and challenges of this innovative concept in the pursuit of climate neutrality and energy efficiency. Through a peer-to-peer analysis of PED case studies and qualitative interviews with key stakeholders in Brussels, Stockholm, Vienna, Évora, Lisbon, and Salzburg, challenges such as the lack of clarity in the definition of PEDs, diversity of ownership, administrative complexity, resistance to change, limited knowledge exchange, financing constraints, technological limitations, and inadequate involvement of relevant actors are identified. Moreover, success factors and enabling strategies from these case studies are highlighted, including clear roadmaps, stakeholder collaboration, integrated decision-making processes, political commitment, and coordination platforms.

1. Introduction

1.1. Pursuing climate neutrality - the Rise of positive energy districts (PEDs)

In response to recent environmental crises, global communities are now prioritizing climate neutrality and minimizing environmental impacts. The urgency arises from commitments to achieve 2030 and 2050 goals, prompting countries to focus on energy efficiency and reduce negative environmental effects caused by climate change.

Various concepts, such as smart cities (Kim, 2022), zero energy districts (Polly et al., 2016), zero carbon neighbourhoods (Nematchoua, 2020), net-zero energy communities (Carlisle et al., 2009), zero energy communities, energy district (Jablonska et al., 2012), and Positive Energy Districts (PEDs) (SETIS, 2018), have emerged to help manage environmental impacts. While these concepts share similar goals, PEDs stand out by aiming for a balance and a surplus of energy generation, creating more energy than needed (Derkenbaeva et al., 2022; European Commission, 2020).

To implement PEDs, communities must re-evaluate their energy generation practices, enhancing resilience against the impacts of climate change (Twigger-Ross et al., 2015). Urban energy system robustness becomes crucial for environmental sustainability, ensuring energy supply reliability and continued access for citizens. Recognizing the

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significant role of cities in the energy transition, PEDs are being developed as key components for energy-efficient environments, a central pillar of international agreements for sustainable development (United Nations, 2015; United Nations, 2017; European Commission, 2021; Zhang et al., 2022).

The PED concept, rooted in the smart city initiative (Gouveia et al., 2021), gained traction with the European Commission launching the PED Programme in 2018 (SETIS, 2018), later revised with targets up to 2030 (Hinterberger et al., 2020). Despite being in the early stages, with only 3.5 % realized as of 2020, PEDs offer valuable lessons for ongoing projects (Turci et al., 2022). Currently, PEDs lack comprehensive terminology for a systematic approach. However, PED is fostering a shift toward a clean, sustainable energy economy as highlighted by studies such as Amaral et al. (2018) and Derkenbaeva et al. (2022). This requires appropriate methodologies and tools specifically tailored to analyse urban-scale districts, as well as appropriate design factors to assess performance at this scale, as Thollander et al. (2010) emphasised. Successful PED projects embrace a holistic perspective, wherein they integrate various elements, including energy generation, efficiency, mobility, and social factors, to attain optimal energy performance (Castillo-Calzadilla et al., 2023). Despite their crucial role in the European Union's climate and energy strategies, PEDs are still gaining recognition on a global scale. The "Clean Energy for All Europeans Package" (European Commission, 2019) serves as the primary regulatory framework supporting PEDs. Despite this, certain international initiatives, such as the District Energy Initiative (Camarasa et al., 2023) and the International District Energy Association (IDEA, 2008), acknowledge and endorse the potential of energy transition on broader scales. In 2020, the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC) launched Annex 83, dedicated explicitly to PEDs. This initiative aims to foster collaboration among international stakeholders and contribute to unlocking the full potential of PEDs (Hedman et al., 2021). Thus, PEDs represent a grassroots response to European and global urban energy transition challenges, as the United Nations (2015) and Sareen et al. (2022) noted.

However, the implementation of PEDs within cities encounters diverse and intricate challenges due to their novelty and the absence of practical experience. Similar to the concept of smart cities, where there is no clear explanation of what makes a city 'smart' and no shared roadmap for defining smartness, PEDs face scepticism and challenges, due to the lack of a unified and precise definition. There is no common agreement on how to achieve positive energy. This ambiguity impacts the initiation, planning, and implementation of PEDs (Amaral et al., 2018; Brozovsky et al., 2021). Such a lack of clarity may lead to scepticism about whether PEDs are merely a buzzword or a genuine promise for creating more sustainable societies.

1.2. Implementing climate targets in the district scale - Challenges to overcome

The implementation of PEDs confronts challenges across various domains, including integrated planning, technological innovation, financing, community engagement, and regulatory frameworks, necessitating collaborative efforts and innovative solutions for success.

The barriers to the widespread implementation of PEDs are multifaceted and include technical capacity limitations, lack of access to advisory services at the local level, limited citizen awareness and engagement, and inadequate resources for public outreach programs. Moreover, interventions in PEDs often occur randomly instead of being part of a comprehensive plan that integrates different measures and sectors. Focusing on individual building-level financing hinders collaborative investments, discourages integrated solutions, and acts as a barrier to adopting non-regret renovation techniques and the success of sustainable, plus-energy neighbourhoods (Erba et al., 2021; Kersens & Greco, 2023). Practical PED experiences are predominantly rooted in new constructions and planning, with limited rehabilitation proposals. Studies addressing heating and cooling demand (Samadzadegan et al., 2021), energy balance and performance (Gabaldon Moreno et al., 2021), densification (Bambara et al., 2021), and PED potential (Laitinen et al., 2021) underscore the importance of spatiotemporal factors, including on-site renewable potential, storage complexities, and social aspects like user behaviour and adaptation.

Efforts to overcome these barriers emphasize involving residents in collaboration (with developers, politicians, investors, and public and private entities), aligning technical improvements with socio-economic benefits, creating new regulations and business models, and planning across various disciplines and domains. Furthermore, overcoming barriers requires addressing challenges associated with interconnected socio-economic, administrative, cultural, legislative, and other perspectives (Thollander et al., 2010; Chai & Yeo, 2012; Palm & Reindl, 2018; Good et al., 2017; Sorrel et al., 2011; Cajot et al., 2017; Cappers et al., 2013; Krangsås et al., 2021).

Solutions to energy imbalances within predefined boundaries depend on the district's capacity to engage with energy networks, consumers, and producers. This applies broadly to all energy carriers but is often specific to electricity, categorized as "off-grid" for isolated units and "on-grid" for connected ones. The distinction between imported and exported energy at district boundaries is termed energy performance (Aghamolaei et al., 2018) (Salom et al., 2021).

Numerous articles propose methodologies and tools for PED transition (Iturriaga et al., 2021), assessing districts (Alpagut et al., 2021; Koutra et al., 2018), decision-making (Congedo et al., 2021; Congedo & Baglivo, 2021), monitoring (Salom et al., 2021; Angelakoglou et al., 2020), and assessing strategies (Natanian & Auer, 2020). However, there is a recognized need for more integrative approaches that leverage and connect existing guides and tools. Currently, the literature in practice is addressing the obstacles associated with deploying PEDs (Koutra et al., 2023; Sassenou et al., 2024; Koutra et al., 2023; Krangsås et al., 2021), through a thorough and critical review, assert that the successful implementation of PEDs necessitates a comprehensive understanding of city priorities, governance and political systems, incentives, social dynamics, and the cultural nuances inherent in stakeholder coordination and engagement within planning and decision-making frameworks.

This study delves into the creation and implementation of PEDs, aiming to uncover their potential and challenges in achieving climate neutrality and energy efficiency. It addresses the lack of precise terminology surrounding PEDs and investigates how the concept has been defined and utilized. Emphasizing the need for clarity and consensus in terminology as PEDs gain momentum, the research seeks to answer the question: How can the challenges and opportunities in the implementation of PEDs inform the development of comprehensive methodologies, governance mechanisms, and tools to achieve climate neutrality and energy efficiency in urban environments? Drawing from the experience and work developed by the authors within the context of an European initiative, COST Action[1] PED-EU-NET, which aims to mobilize researchers and practitioner communities across different urban domains to drive the deployment of PEDs in Europe through open sharing of knowledge, exchange of ideas, pooling of resources, experimentation of new methods, and co-creation of novel solutions. By examining real PED cases in European urban districts, including Vienna, Brussels, Stockholm, Salzburg, Lisbon, and Évora, the study aims to uncover valuable insights and lessons for future. The article is organized with Section 2 outlining the research methodology, Section 3 describing all

[1] COST (European Cooperation in Science and Technology) is a funding organization for research and innovation networks. COST Actions are bottom-up networks with a duration of four years that boost research, innovation, and careers by connecting research initiatives across Europe and beyond, enabling researchers and innovators to grow their ideas in any science and technology field by sharing them with their peers.

case studies, Section 4 discussing key findings, and Section 5 concluding the paper while highlighting potential areas for future research, emphasizing the ongoing exploration and development of PEDs for resilient and sustainable cities. Fig. 1 presents the flow diagram that clarifies the study process that has been developed in this study.

2. Methodology

2.1. Qualitative multiple case-study research

We conducted qualitative multiple case-study research to gain a deeper understanding of cities' perspectives on PEDs and identify the challenges they face in implementing PED strategies. The rationale behind choosing a qualitative approach is that researching these challenges requires capturing individuals' views and assessing the planning and decision-making processes influenced by various social, institutional, and political settings that change over time. The goal is to generate insights into sociocultural relationships, understanding, and representation of experience/knowledge, as well as to present and explain the context in which these experiences are located. This information collection has been carried out through a feedback process between the interviewees and the interviewers, processing the data at each step and verifying the results with the stakeholders. This process is based on the identification of case studies representing different contextual situations, although all these cases should have some funding sources and be in the implementation phase to provide data on the implementation process. Another key requirement is the cooperation of different stakeholders to register different points of view, as well as to have access to information from the case studies. Fig. 2 shows this iterative process used to collect the data.

The qualitative approach allows us to focus on the meaning of individuals' explanations and viewpoints rather than their quantification. This approach helps us understand the characteristics of the situation in depth and enables us to unravel the complexities of interconnected and interrelated structures and processes inherent in the PED concept.

A multiple case study method was chosen as it provides sufficient details to explore the complexities of each situation. This method allows us to uncover how different variables affect one another and identify patterns in the process of initiating, designing, planning, implementing, monitoring, and exchanging knowledge in PED projects. By comparing and finding similarities and differences between cases, we can understand the uniqueness of their contexts. Moreover, the multiple case study approach enables us to collect diverse experiences, perspectives, interpretations, and ideas from various stakeholders involved in PED projects. This broad range of inputs helps us identify both technical and non-technical tools needed to overcome the challenges.

2.2. Data collection

The data was collected through semi-structured, in-depth interviews with an open framework. This interview method was chosen because it allows for focused, conversational, two-way communication that facilitates the sharing and receiving of information. It allows interviewees to elaborate on points of interest, enabling a close collaboration between the researchers and the interviewees. The semi-structured nature of the interviews allows informants to express their views in their terms, resulting in more reliable and comparable qualitative data.

Convenience sampling, a non-probability sampling method, was selected to choose the interviewees. The researchers of this paper were involved in relevant PED projects and initiatives, which provided accessibility and networks for selecting informants. Based on these available networks, a selection of case studies was made according to several requirements:

- Diversity of situations: Various climatic zones and urban developments (new construction and rehabilitation) were considered to cover various districts. Aspects such as regulations and standards were particularly important in this selection.
- Funding to implement the measures: The districts studied are funded by international or national projects on Positive Energy Districts.
- District implementation: The project's implementation should be at an advanced stage of development or close to completion. It is desirable to have information on the most and least successful aspects.
- Public information: The willingness of the interviewees to provide openly published and accessible information.

The final selection was made based on the willingness of stakeholders to participate in this study. Due to PEDs' relatively recent emergence, dedicated PED projects are limited, and many are in early planning phases. To focus the study, cities actively engaged in Positive Energy District (PED) initiatives, such as Vienna, Brussels, and Stockholm, were concentrated on through projects like 'cities4PEDs' and the Synika Project in Salzburg, where significant progress was showcased.

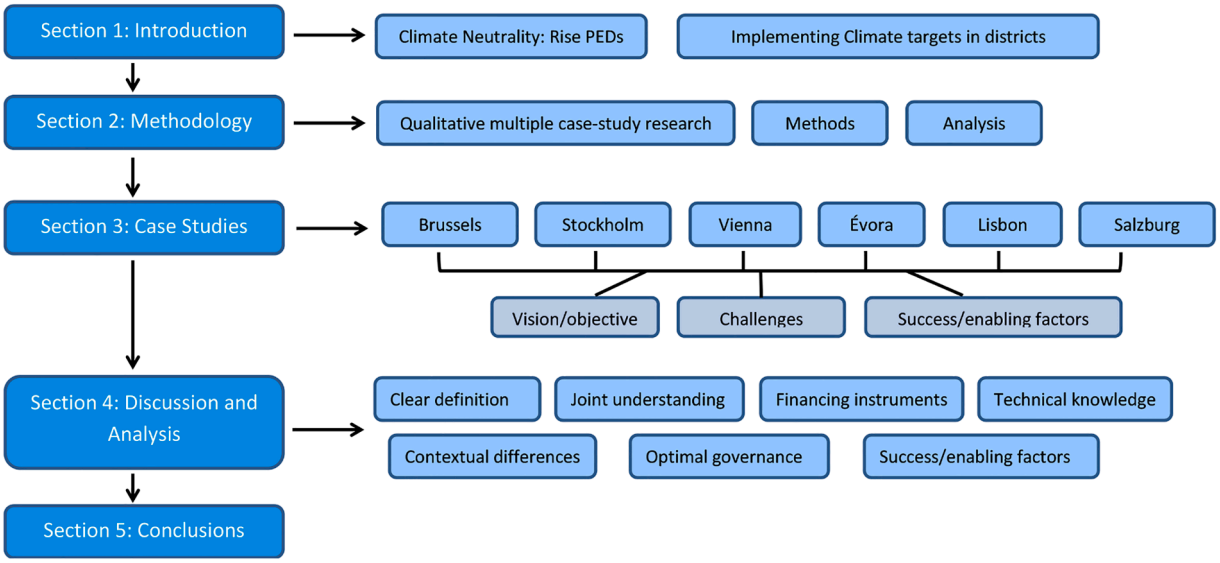

Fig. 1. Flow chart of the sections implemented in this study.

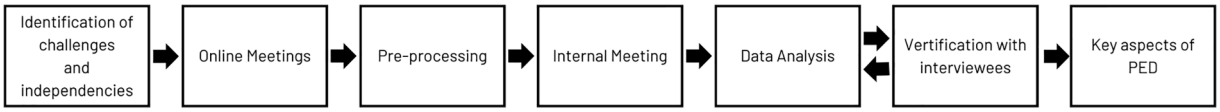

Fig. 2. Iterative process used to collect the information from the stakeholders.

Leveraging the COST Action network, a snowballing method was employed to identify cities with extensive PED knowledge, which led to the inclusion of Lisbon and Évora in Portugal.

Also, the case studies selection aims to capture a diverse array of European urban contexts while maintaining certain similarities that facilitate comparison. These cities span across North, Central, and South Europe, offering insights into how PEDs adapt to various climatic conditions. These locations within Europe share a cultural, regulatory, and developmental context, particularly regarding renewable energy technologies, infrastructure, and a general awareness of sustainability issues. This similarity allows the study to focus on local implementation processes without the need to account for vast differences in technological access or cultural attitudes towards energy efficiency and climate change. The chosen cities represent a mix of capital cities and smaller towns, industrialized areas, and regions known for tourism, ensuring that the study's findings are broadly applicable across various urban settings. The collection of information provided by the case studies generated multidisciplinary and heterogeneous data, making the analysis methodology difficult. Therefore, an iterative process was carried out that fostered a dynamic and collaborative approach, enriching the information obtained.

The interviewees were invited based on their leadership and experience in PED-related projects, aiming to represent the forefront of PED implementation in Europe. Key stakeholders from different European cities were asked to share their story, emphasizing the process from the initial idea to the actual realization of a PED. The storytelling method was employed during the in-depth interviews to allow interviewees the freedom to tell their stories meaningfully. They were encouraged to describe their involvement, the timing and reasons for their involvement, and their perspectives on the challenges and strengths of the project strategies, processes, and concepts. By employing this methodology, we aimed to thoroughly understand cities' perspectives on PEDs, identify their challenges, and contribute to creating guidelines and/or roadmaps for successful PED implementation. Combining qualitative case studies and semi-structured and storytelling interviews allowed us to gather rich and diverse data, ensuring a comprehensive exploration of the complexities and nuances of PED implementation. Table 1 provides information about the selection criteria and the interviewees involved in PED cases. It should be noticed that all these cases belong to European projects that are being implemented or about to be completed.

2.3. Data analysis

To comprehensively understand and analyse the challenges and characteristics of PEDs from multiple perspectives, our analysis encompasses various steps. Firstly, we aim to gain insights into the diverse meanings and interpretations of PEDs among interviewees, examining whether creating PEDs is a primary objective or a supplementary approach for cities. We investigate the initiation of PED processes/projects to understand the underlying challenges, considering the perspectives of interviewees with diverse scientific and professional backgrounds and roles in the projects. Additionally, we identify any overlooked challenges from the researchers' perspective. Furthermore, we explore each case's strengths and success factors, seeking valuable lessons that can be replicated or learned from. By conducting a pattern-matching analysis across the cases, we aim to develop a comprehensive exploration of the complexities and nuances of the early-stage planning and implementation of PEDs. This analysis approach enables us to provide a broader perspective and a bigger picture rather than a narrow theoretical framework. Moreover, by bridging the gap between theory and practice, our analysis fosters a dialogue that can contribute to advancing PED concepts and procedures.

In addition to our comprehensive analysis of the interviews, the paper underwent a review process by the interviewees to ensure that our interpretation and understanding of the interviews were aligned with their intended meaning and the context of the paper. This review encompassed an assessment of our quoting accuracy and the usage of information derived from the interviews to ensure fidelity to the participants' perspectives. Furthermore, this review provided the opportunity to incorporate any new information about the ongoing projects, reflecting their evolving nature. We obtained feedback from all our case studies except those in Salzburg and Stockholm. The process of analysis and interpretation of the data is shown in Fig. 3.

3. Case studies

The evaluated cases span four European countries located in different regions (see Fig. 4): Portugal (south), Austria and Belgium (centre), and Sweden (north). These countries exhibit diverse climatic zones: Csa (dry and hot summers, humid and temperate winters), Cfb (moderate oceanic climate), and Dfb (cold winters, hot and humid summers) (Kottek et al., 2006). All of the analysed cases were part of European projects or initiatives aimed at improving the sustainability and energy transformation of cities, often combining European funding with local and national sources. These projects focused on enhancing the energy efficiency and climate neutrality of existing urban areas and new developments. Understanding the sources and allocation of funding (EU, national, or local) and its type (research, public funding, other) provides valuable insights into the feasibility and sustainability of such projects.

Among the cases, three were associated with the Cities4PEDs project (Brussels, Stockholm, Vienna), one with the POCITYF H2020 project (Évora), one with the Syn.ikia project (Salzburg), and one with multiple European projects, including Sharing cities and SusCity-MIT (Lisbon), which also received the European Green Capital Award. To gain a comprehensive understanding of the transformation process, synergies, challenges, and lessons learned, it is important to consider the contextual factors of each case, such as location, climate conditions, and specific urban development characteristics. The Köppen-Geiger classification was used to describe the climate zones based on temperature, precipitation, and seasonality, providing a framework for comparing and analysing the cases (see Table 2).

The first three cases (Stockholm, Vienna, and Brussels) in our study are part of the Cities4PEDs project, which focuses on the legal, institutional, and organizational aspects of PEDs by integrating research, innovation, and citizen participation. This non-profit city network aims to explore how cities can adapt their planning and implementation strategies to create neighbourhoods that generate more renewable energy than they consume and enable more flexibility in the power grid. The rationale for selecting the Cities4PEDs project is twofold. Firstly, the project's title aligns with our focus on PEDs. Secondly, the chosen districts within these cities offer diversity, including existing and newly constructed areas, each presenting unique challenges such as energy poverty, coastal vulnerability, and significant social housing development.

The city of Lisbon aims to develop positive energy neighbourhoods through the improvement of construction conditions for buildings and the integration of renewable technologies in an area with patrimonial requirements.

Table 1
Selection criteria and overview of interviewees.

Case	Location Europe	Urban developments	Interviewee role/Organization	Involvement in the PED
1.Brussels	Centre	Refurbishment	Coordinator of the project "Cities4PEDs"/Architecture Workroom Brussels	Project "Cities4PEDs" (JPI Urban Europe funding program). Brussels is a case study.
2.Stockholm	North	New construction	Sustainability Strategist + *R&D* Coordinator/City of Stockholm	Project "Cities4PEDs" (JPI Urban Europe funding program). Stockholm is a case study.
3.Vienna	Centre	Refurbishment + new construction	Expert/Urban Innovation Vienna	Project "Cities4PEDs" (JPI Urban Europe funding program). Vienna is a case study.
4.Évora	South	Refurbishment	Coordinator of the project "POCITYF"/EDP Labelec	Project "POCITYF" (Horizon, 2020 funding). Évora is a Lighthouse City.
5.Lisbon	South	Refurbishment	Associate Professor/Técnico Lisboa	Multiple projects "Sharing cities" and "SusCity-MIT" (European and Portuguese funding).
6.Salzburg	Centre	New construction	Housing Researcher/SIR Salzburger Institut für Raumordnung & Wohnen	Project "Syn.ikia" (Horizon, 2020 funding). Salzburg is a Demo project.

The case of Évora is part of the European project POCITYF H2020, whose main objective is to improve the performance of historic cities towards greener, smarter, and more liveable models while respecting their cultural heritage. To this end, urban models are being designed to enable this transition by combining high renewable energy ratios with Positive Energy Blocks, integrating e-mobility, innovative ICT technologies, and citizen engagement strategies. Additionally, this project aims to develop a network that brings together cities with cultural heritage and efficient and sustainable behaviour, in which municipal administrators, planners, universities, businessmen, and citizens participate.

Finally, the case of Salzburg is part of the European project Syn.ikia, whose main mission is to increase the proportion of sustainable neighbourhoods with surplus renewable energy in different contexts, climates, and markets in Europe. The project also encourages community participation, the use of digital platforms, increased housing affordability, improved quality of life, and greater environmental awareness, key aspects in bringing about change in the behaviour of citizens and their cities. The following part provides a better description of each case study, which follows the points: a brief description of the project, vision and objective, challenge, success, and enabling factors.

3.1. Case 1: Brussels

3.1.1. Vision/Objective

Brussels aims to transform its area into a PED by facilitating the energy transition, testing local renewable energy projects, implementing social cohesion and involving citizens. Their objectives include becoming fossil fuel-free, reducing greenhouse gas emissions, and achieving carbon neutrality.

3.1.2. Challenges

Ownership diversity and complexity: the wide dispersion of individual homeowners and small business owners, the high presence of tenants in the district, and the variety of their responsibilities make it difficult to build consensus around potential local measures. A possible facilitator to help solve these problems could be the city administration itself.

Mistrust of residents towards the government: Residents have seen many different processes of radical, top-down urban renewal in the area over the last few decades, and this has made them more reluctant to be involved in the process of change in the area.

Transitioning from individual energy systems to collective ones: The prevalence of predominantly individual energy systems, primarily centred around individual gas boilers, underscores the necessity of engaging various homeowners to initiate the adoption of inventive collective solutions. Such initiatives can foster the evolution of decentralized, self-sustaining local energy systems. This challenge involves addressing both the technical complexities of energy transition and the social dynamics required to drive collaborative change within communities.

Administrative complexity of Belgium and limited local government capacity: requiring the necessity of cooperation and coordination between different administrative bodies and their ongoing projects at the local level. By creating synergies and connecting various interventions and plans within a neighbourhood, integrated and efficient district solutions can be achieved. Additionally, "energy communities" can serve as examples of initiatives that align with the goal of integrated solutions, where different stakeholders collaborate to develop comprehensive approaches to energy management and sustainability at the district level.

Lack of technical knowledge about PED: Influential actors, often including politicians or individuals with political influence, whose support is highly beneficial when implementing an efficient and sustainable solution in an urban environment, may lack the technical understanding of PED. However, their support remains crucial for the successful implementation of effective and sustainable urban solutions.

Additional Challenges: Other challenges include balanced

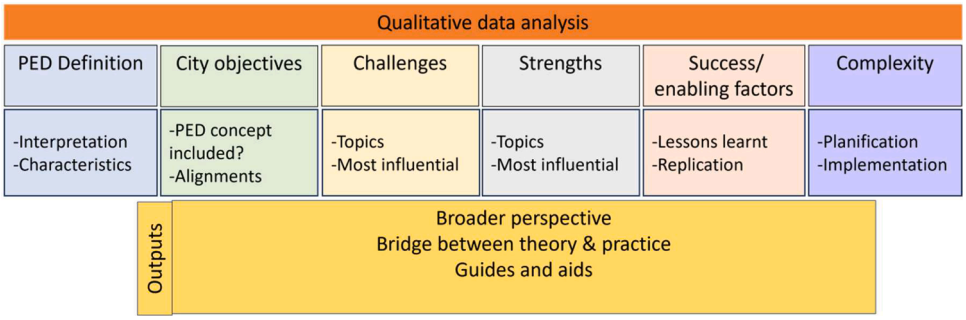

Fig. 3. Data analysis and interpretation scheme.

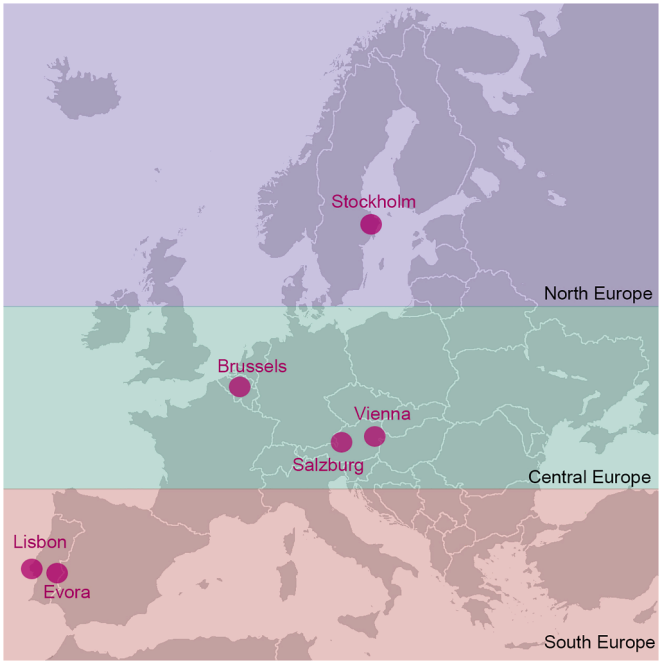

Fig. 4. Location of the studied cases in Europe.

involvement between users and municipalities, difficulty in attracting private investment, segmentation and lack of cooperation between actors involved in the decision-making process, and land contracts.

3.1.3. Success/Enabling factors

Brussels has achieved success by forging coalitions between the city administration, local social organizations, private building owners, the energy provider, and more. This collaborative approach takes into account social and economic dimensions. In this context, energy, including PED, is perceived as a tool to enhance the community's quality of life and tackle various local issues like housing standards and employment opportunities. Yet, despite these strides, the essential aspect of citizen involvement remains to be fully incorporated.

3.2. Case 2: Stockholm

3.2.1. Vision/Objective

The vision of Stockholm is to eliminate the use of fossil fuels by replacing them with renewable sources and reducing overall energy consumption. The city aims to enhance energy efficiency and promote local production of renewables. While becoming energy positive is not the primary goal due to financing challenges, Stockholm focuses on transitioning to a sustainable energy system.

Table 2
The PED cases of the study.

Cases		Urban proposal	Main goals	Funding
Brussels Belgium	Cfb	Already-built Northern District	First Positive Energy District, linking energy targets with biodiversity and smart city ambitions	National and local public funding, membership fees and EU funding
Stockholm Sweden	Dfb	Newly built area within the Stockholm Royal Seaport	Become fossil fuel free	National and local public funding, membership fees and EU funding
Vienna Austria	Cfb	Pilzgasse as new area; Seestadt Aspern as urban expansion area; Stadtquartier Muthgasse as an existing structure with new buildings and Otto Wagner Areal as refurbishment of an existing district	Promote climate neutrality in 2040 locally and nationally	National and local public funding, membership fees and EU funding
Évora Portugal	Csa	Refurbishment of a heritage area	Improve the city's energy landscape	H2020 Program
Lisbon Portugal	Csa	Transformation of existing neighbourhoods	Sustainable urban transformation	European and Portuguese funding
Salzburg Austria	Dfb	New sustainable urban development	Positive energy urban development	H2020 Program

3.2.2. Challenges

Mindset and Resistance to Change: Some actors are resistant to change and reluctant to step out of their comfort zone, hindering the progress of PEDs. Limited knowledge exchange and sharing of experiences among developers further contribute to this challenge.

Lack of Procurement for Developers: The absence of proper procurement mechanisms poses a challenge for developers in implementing PED projects effectively.

Technological Limitations: Existing technologies do not allow for the physical creation of PEDs. Additionally, connecting energy production between different regions of Sweden, such as the North and South, remains unresolved.

Contextual Factors: Selecting the appropriate areas or districts for PED implementation requires careful consideration of contextual factors such as renewable potential and geographical situations.

Additional Challenges: Other challenges include residual waste management in district heating systems, seasonal storage of electricity, sub-optimization at the building level, and overcoming the resistance of

the construction industry towards supporting PEDs. Insufficient funding and the issue of greenwashing further complicate the achievement of PED goals.

3.2.3. Success/Enabling factors

Stockholm's success in implementing PEDs lies in its capacity building plans and the involvement of relevant and influential actors, particularly developers who are encouraged to work with energy efficiency and the green space index. This comprehensive engagement ensures a more holistic approach to sustainable urban development and supports the replication of successful strategies and practices in other cities.

3.3. Case 3: Vienna

3.3.1. Vision/Objective

The City of Vienna envisions triggering innovative projects in social neighbourhoods, urban renewal, and public spaces. Simultaneously, it strives to achieve climate neutrality by 2040 through a comprehensive decarbonisation strategy to address the city's social, economic, ecological, and governance challenges.

3.3.2. Challenges

Vagueness of PED concept: The lack of a joint definition and clarity surrounding PEDs, coupled with the dominant perspective of Vienna aligning with the smart city strategy, complicates the implementation of PED projects.

Interaction with stakeholders: Indeed, the misalignment between the perspective of city planners, who set the vision and goals of the city, and those actors who are responsible for implementing the plans and possess technical knowledge can lead to significant challenges. Effective dialogue and alignment of perspectives between these different actors are crucial to ensure successful and harmonious development and implementation of PEDs.

Financial challenge: There is a need for financial instruments to implement PEDs, and convincing the private sector to invest in these urban models is a great challenge, as there are higher upfront costs than in usual real estate projects.

Activation and engagement of citizens: the importance of involving citizens from the beginning phase, as well as building trustful and reliable relationships between citizens and local authorities, is acknowledged. However, the strategy for realizing a participatory process should be developed further.

Additional challenges: Other challenges include regulatory and social issues, optimized market integration of renewable energies or designing business models adapted to the urban context.

3.3.3. Success/Enabling factors

The city's success factors lie in its attention to involving local stakeholders, engaging citizens from the beginning of decision-making processes, utilizing local organizations as intermediaries and setting strong and clear targets on a strategic level.

3.4. Case 4: Évora

3.4.1. Vision/Objective

Évora has been implementing its Sustainable Energy Action Plan (SEAP) since 2012, aiming to reduce energy consumption and CO2 emissions, and promote sustainable energy utilization.

3.4.2. Challenges

Fulfilment of heritage requirements: It is necessary to find innovative solutions that can be integrated into the city's landscape taking into account the requirements and constraints of cultural heritage areas.

Involvement of stakeholders: Local authorities and politicians must be involved at all levels of intervention, from the lowest to the highest positions, and in different phases of implementation. Meeting this challenge would facilitate the acceptance of innovative solutions.

Administrative limitations: The time required for administrative procedures and acceptance of solutions in heritage protected areas must be reduced in order to implement them properly. These types of solutions require approval from local and national administrations.

Flexible technological solutions: To achieve high energy efficiency and self-consumption in these areas, it is necessary to increase the capacity for energy exchange between buildings and surrounding areas with distribution networks and electric vehicle charging stations.

Financial instruments: The implementation of technically and economically viable solutions requires an increase in available funding instruments.

Additional challenges: other challenges include regulatory and legislative aspects of solar farms, PV integration in the urban context, and yearly negotiation of municipal budget to implement these initiatives.

3.4.3. Success/Enabling factors

Évora's success factors include an online citizen platform for discussion and proposals, involvement of technicians and citizens through workshops, and the role of local administration as a link between technicians and citizens.

The enabling factors that can help Évora could be the co-creation process that combines energy, cultural, social, governance and heritage aspects with the interests of the different stakeholders, achieving the commitment and involvement of administrations from the highest to the lowest levels. This requires aligning the political agenda, citizens' interests and knowledge about PEDs.

3.5. Case 5: Lisbon

3.5.1. Vision/objective

Lisbon focuses on transforming a social housing neighbourhood into a PED by exploring solar energy systems, energy flexibility, and the consumer-side provision of flexibility.

3.5.2. Challenges

Grid Capacity for Mixed-Use Buildings: Diverse or mixed buildings present unique technical challenges when it comes to managing energy and grid capacity. Such buildings often have varying energy demands, usage patterns, and equipment requirements, making it complex to optimize energy distribution and ensure grid stability. Balancing the diverse energy needs while maintaining the grid's capacity requires advanced solutions and technologies that can adapt to the dynamic nature of these buildings and effectively manage the overall energy infrastructure.

Urban Energy Modelling tools: Using a tool capable of simulating multiple buildings within a district is crucial, as relying solely on tools designed for simulating individual buildings may not yield reliable results. Back in 2015, when the project began, only a limited number of urban energy modelling tools were accessible.

Regulatory aspects and regulation of optimal technical solutions: Regulatory aspects set guidelines for designing and implementing energy systems, promoting the use of optimal technical solutions. Regulatory frameworks play a pivotal role in shaping the development of such districts and driving their long-term success.

Various actors and their different interests: Stakeholders such as residents, developers, utilities, and local governments often have different priorities and objectives. Harmonizing these interests and reaching a consensus becomes crucial for successful project implementation. Effective communication, collaboration, and negotiation are essential to ensure that diverse perspectives are addressed.

Implementation speed and efficacy: Slow implementation compared to population growth and technology development is a challenge to be addressed. The long implementation period resulted in the population expanding and new technologies emerging, the projects may struggle to

keep up with the increasing demand and evolving energy needs.

3.5.3. Success/Enabling factors

Success factors for Lisbon include collaborative multidisciplinary research projects, extensive characterization of building stock, and the use of simulation tools and digital platforms for decision-making.

3.6. Case 6: Salzburg

3.6.1. Vision/objective

Salzburg's vision is to achieve CO2 neutral energy supply for a neighbourhood, with a strong focus on social sustainability and cooperative planning processes. Salzburg's long-term plan for sustainability and its commitment to the city's political leadership can contribute to the realization of this vision.

3.6.2. Challenges

Governance challenge and need for a coordinator: With multiple stakeholders involved, coordinating their efforts, aligning interests, and making collective decisions can be complex. A dedicated coordinator serves as a central point of contact, facilitating communication, fostering collaboration, and ensuring effective governance structures are in place to navigate the complexities and drive the success of positive energy district projects. The coordinator should also deal with budget restrictions and funding as a door opener for the project.

Dependence on people with diverse interests: PED projects involve people with diverse interests and motivations. Some individuals may be driven by environmental concerns, aiming to reduce carbon emissions and promote sustainability. Others may be motivated by energy benefits, seeking energy savings or new related business opportunities. Understanding and addressing these varied interests is crucial to engaging and fostering widespread participation in PED initiatives, creating a shared sense of ownership and ensuring the projects' long-term success.

Change of acting person during the project: The planning and implementation phase of district-related projects requires a long time and during this period the acting person may change sometimes. Therefore, having an appropriate vision and planning process is very crucial.

Fairly share of funding and produced energy among citizens: Ensuring fair distribution of finances and benefits among all citizens is essential. Creating an energy community fosters equitable sharing of both financial responsibilities and energy resources while encouraging active participation from all citizens involved in the community.

3.6.3. Success/Enabling factors

The success of the Salzburg case can be attributed to the provision of an integrated solution that encompasses green initiatives, community support, and an efficient energy source. This noteworthy accomplishment is a result of a collaborative planning process that ensured the active involvement and participation of various stakeholders. Key to the success is the role played by the Institute for Regional Planning and Housing (SIR), acting as a crucial coordinator managing the diverse aspects of the project.

Several enabling factors contribute to Salzburg's ability to overcome its challenges. First and foremost, the city requires a clearly defined roadmap that outlines the necessary steps to achieve a common goal. It is imperative that this roadmap is developed collaboratively and agreed upon by all stakeholders involved in the project.

In dealing with complex projects like area redevelopment, the involvement of external experts becomes essential. These experts bring specialized knowledge and experience to tackle the intricacies of the project. Notably, EU funding has played a pivotal role in supporting such roles, recognizing their significance beyond the standard governmental process. To further enhance efficiency and effectiveness, it is recommended that the coordinator and external experts operate independently of the government. This separation ensures unbiased guidance and recommendations, promoting a more objective and holistic approach to decision-making.

4. Discussion and analysis

4.1. Lack of clear definition

Delving into the interviews and stories shared by the representatives of PED cases, it becomes evident that each city faces unique challenges and opportunities in their pursuit of sustainable urban development. However, these projects were not initially conceived as PED implementations, their main objectives were to drive energy transformation and climate neutrality in European cities. They share a common vision of transitioning towards renewable energy sources, reducing carbon emissions, and enhancing energy efficiency. PED is perceived as a facilitating tool or concept to achieve the overarching goals, often driven by research projects, particularly those funded by the EU. The lack of specificity in defining urban models posed a significant barrier to defining or replicating a PED.

However, the path to achieving these goals is paved with obstacles that require careful consideration and strategic planning. Through comparative analysis and a peer-to-peer perspective, this discussion aims to delve deeper into the challenges encountered by each city, identify common patterns, and explore potential strategies and enabling factors that can contribute to the successful implementation of PEDs. By learning from one another's experiences, these cities can collectively strive towards a greener, more sustainable future. The comparative insights, including the factors that have hindered or facilitated the implementation of various PED concepts, are presented in Table 3, outlining the primary conclusions drawn from the six case studies in different contexts.

4.2. Unfamiliarly and lack of joint understanding

One common challenge that arises across our multiple cities is the resistance to transforming the prevailing mindset among different stakeholders and entrenched practices towards embracing sustainable energy solutions and recognizing the importance of PEDs among various actors. In Stockholm, for instance, some stakeholders are resistant to stepping out of their comfort zones, hindering the progress of PEDs. This resistance is compounded by limited knowledge exchange and a lack of sharing experiences among developers. Similarly, Vienna struggles with a lack of understanding and definition of PEDs, which hampers the city's perspective on becoming a PED. Overcoming these challenges necessitates active engagement and education to foster a mindset shift and create a shared understanding of the benefits and importance of PEDs among stakeholders. To this end, several tools can be used to improve social awareness and increase stakeholder involvement through different categories of workshops or citizen platforms. The application of these measures has been successful in cities such as Évora.

4.3. Lack of financing instruments

Financial considerations also emerge as a recurring challenge. Several cities, including Vienna and Salzburg, face difficulties in providing suitable financing instruments to support the implementation of PED projects effectively. The absence of proper procurement mechanisms further exacerbates the challenges faced by developers. It's worth noting that the issue doesn't solely pertain to the city itself in Vienna; rather, the root of the problem lies in the calculation methods and business models of private developers, as outlined in Table 3.

4.4. Lack of technical knowledge

Technological limitations present another significant obstacle for PED implementation. Stockholm highlights the limitations of existing

Table 3
Identified objectives, challenges and enabling factors of PED cases.

	Stockholm	Vienna	Brussels	Lisbon	Évora	Salzburg
Main objectives	Technical & economic aspects	Social innovation & governance factors	Social, governance & economic factors	Transformation process & technical aspects	Governance & regulatory aspects	Governance & social aspects
Blocking factors	Low local RES production Involve construction companies	Citizen acceptance, lack of business models	Complex financing instruments, disperse ownership structure, need of diversified local capacities	Low involvement of developers to increase financing instruments	Low consideration of heritage requirements from the beginning	Involvement of inappropriate agents according to the phases of the project
Success factors	Political commitment	Collaboration of local Stakeholders	Strong network and coalition between different actors	Consideration of different interests in decision-making process.	Online citizen platform	An integrated solution that encompasses green initiatives, community support, and an efficient energy source and successful collaboration
Enabling factors	Holistic systemic change	Citizen participation methods and approaches	Citizen participation methods and approaches	Digital platforms for decision-making	A real co-creation process	A defined roadmap and involvement of external experts

technologies in physically creating PEDs, while Brussels emphasizes the need to investigate collective and decentralized solutions for local renewable energy systems regarding the prevalence of individual energy systems. Lisbon comments on the difficulty of connecting some areas of the city to district networks. While Évora highlights the difficulty of finding innovative solutions that meet heritage requirements. To solve these problems, it is necessary to improve the capacity, flexibility and accessibility of existing infrastructures, thus enabling more efficient management of all urban flows. These technological challenges require continuous research and development efforts to advance the capabilities of renewable energy systems, storage solutions, and grid integration. Furthermore, interconnecting energy production between different regions within a city or country, as seen in the case of Stockholm, poses additional complexities that must be resolved through collaborative efforts and innovative solutions.

According to the interviews, one of the main challenges is maximizing the use of renewable energy sources in the country and implementing energy efficiency measures while considering the region's unique characteristics and constraints, e.g., renewable potential, geographical situations, and existing infrastructures. To meet the energy needs of a district, it is important to produce as much energy as possible. However, different countries have different approaches to achieving this goal, and connecting these approaches remains a challenge. Strategies to address this challenge include maximizing the use of electrical storage, building renovation, and installing renewable energy sources. Increasing local renewable penetration enhances district energy self-sufficiency and enables flexibility for peer-to-peer trading, congestion management, and other non-frequency services to distribution system operators (DSOs), wholesale markets (day-ahead and intraday), and even ancillary services markets. Lisbon's experience with technical challenges in diverse/mixed buildings and grid capacity highlights the importance of understanding and adapting to the unique characteristics of the built environment. Thus, retrofitting protected buildings with renewable energy sources requires viable technical solutions that consider heritage, social, regulatory, and legal aspects. In addition, as suggested by Évora, "there is a need to engage citizen to accept the solutions and make them understand that it will not spoil their local buildings, and ultimately their culture".

4.5. Contextual differences inhibit lesson exchange

Contextual factors such as the district's transition to PED, diversity of ownership, and the actor network also play a crucial role in determining the success of PED implementation. There is a lack of expertise, knowledge exchange, experience sharing, and procurement, and the contextual differences between cities challenge the lesson exchange between them. Considering their contextual factors, cities need to tailor their PED strategies to maximize the utilization of renewable resources and ensure optimal energy efficiency.

4.6. Lack of optimal governance

Problems arising from poor governance, such as conflicts, unclear interests and agendas, power asymmetry, etc., pose challenges. Governance engagement levels are currently low and need to be increased to incorporate more individuals. Ensuring the involvement of influential actors, such as developers with financial resources and market expertise, can be a valuable solution. Suggested by the Stockholm case, to foster optimal governance in the development process, developers' input can bring valuable insights and help align the project with market realities and stakeholders' interests.

Uncertainty and ambiguity in planning and decision-making processes due to a lack of knowledge and resources, particularly in the context of PED, can increase challenges. Municipal interests or political agendas may determine site choice rather than technical aspects. Lengthy bureaucratic and political processes can demotivate citizens.

Municipal hierarchies can complicate the decision-making process due to a lack of communication. There may be a low transfer of knowledge.

In addition to these shared challenges, each city faces specific issues that are intrinsic to its local context. For example, Brussels encounters a diversity of ownership and complexity in combining interests and responsibilities, necessitating effective stakeholder management and coordination. Évora, on the other hand, focuses on integrating sustainable energy solutions while respecting the city's cultural heritage, requiring innovative approaches that balance preservation and modernization. Évora discussed that site selection in such heritage city is often influenced by political or municipal agendas that may not align with the physical feasibility of creating PEDs. In addition, the approach of having a preconceived solution and then searching for a problem to fit was mentioned as another challenge and misguided path to take. It was explained that this path neglects the fundamental principles of problem-solving and innovation. The natural way to address a problem or challenge is to first identify it and then delve into its roots, gaining a comprehensive understanding from multiple angles. Lack of focusing on understanding the problem and its underlying complexities can lead to suboptimal outcomes and ineffective solutions that do not truly address the core issues. Moreover, it disregards the importance of innovation and creativity in problem-solving. It limits the exploration of alternative approaches and innovative ideas that could potentially lead to breakthrough solutions.

Salzburg, in its pursuit of a CO_2-neutral energy supply for a neighbourhood, emphasizes the need for a clear roadmap and common goal, along with effective governance and coordination facilitated by a dedicated coordinator.

4.7. Success and enabling factors

Despite challenges, success factors and enabling strategies emerge from the experiences of these cities as shown in Table 3. Stockholm's comprehensive engagement with influential actors and capacity building contributes to a holistic approach to sustainable urban development. Vienna's focus on the involvement of local actors and co-creation harmonizes interests and encourages active participation. Lisbon showcases the benefits of collaborative multidisciplinary research projects and simulation tools, leveraging technology and knowledge-sharing platforms for decision-making. Évora highlights the importance of a co-creation process with the participation of the municipality, academia and citizens. Furthermore, Brussels' progress is attributed to the balanced involvement of citizens and municipalities, coupled with a focus on renewable energy optimization and socio-economic aspects.

Enabling factors to overcome challenges include having a clear and concrete roadmap proposing efficient and integrative solutions, coordinating implementation through a body that considers the interests of all involved actors, and aligning energy, cultural, social, economic, governance, and heritage aspects with stakeholder interests. The commitment and involvement of administrations, citizens, businesses, and funding bodies are crucial. Establishing a coordination platform or organization, utilizing online platforms for communication and collaboration, disseminating good practices through campaigns, and raising awareness among administrations, financial companies, and citizens about the benefits of district solutions are driving factors. Participation in research projects and the gained experience, capacity, and support are also success factors. Coordination platforms like SIR in Salzburg act as external bodies aligned with management and coordination tasks, while in other cases like Évora, online platforms serve as supportive tools for communication and collaboration. In Brussels, the Coordination Platform sought to test a new form of governance to facilitate the process of local transformation in the form of an informal table bringing together the various stakeholders to start building together the common foundations for a long-term strategy and the concept for energy pilot projects in the Northern District

A peer-to-peer analysis of PED case studies highlights the complex and multifaceted nature of implementing Positive Energy Districts. Overcoming mindset barriers, securing adequate financing, addressing technological limitations, considering contextual factors, and tailoring strategies to local contexts are essential for success. By learning from one another's experiences and sharing best practices, these cities collectively strive towards sustainable and energy-positive urban environments. Fostered by open dialogue, shared ownership, and diverse perspectives, stakeholder engagement overcomes resistance, builds consensus, and fosters collective responsibility towards PED goals. Through continued collaboration and knowledge exchange, challenges can be transformed into opportunities, fostering innovation and paving the way for a greener and more sustainable future.

To address this, cities should explore innovative funding models and establish partnerships with public and private entities to ensure adequate financial resources for PED initiatives. Ultimately, our discussion emphasizes the need for transformative shifts in thinking and the importance of inclusive collaboration to overcome barriers and drive sustainable change in urban development.

Replicable factors identified in the case studies, with varying people interaction across phases, include collaborative, coordinated, and multi-sectoral work from the early stages, considering the interests and objectives of stakeholders. Governance emerges as a key challenge, and developing an effective model can be a solution. Proposals should be structured and coordinated by a steering committee led by the local administration, with the participation and collaboration of all urban actors at all levels. Involving local organizations as intermediaries with citizens has proven helpful, exemplified by entities like SIR in Salzburg, whose roles and contributions need legitimization by different actors.

Written documentation and websites support idea exchange, decision-making, and dissemination. Integrated and comprehensive urban models assist in designing and optimizing energy and economically viable solutions. Existing information platforms in cities can be utilized to implement integrated solutions that enable energy and sustainable district transitions.

Clear definitions and requirements for implementing PEDs are necessary to align project objectives with city transformation processes, addressing the lack of clarity and specificity and avoiding overlap with other sustainable urban models.

Once this qualitative study is completed, its results will be combined with the information from the PEDs and PED Labs database generated within Cost Action (Turci et al., 2022). This combination will provide information on decision-making and planning processes as well as on different aspects of the operation, assessment and management of the case study, generating a database whose processing will facilitate the development of new guidelines and methodologies useful for future implementations, developments and replications of a PED.

5. Conclusion

Our paper makes a substantial contribution by uniquely identifying the genuine challenges addressed by key stakeholders in various PEDs. Our findings reveal a significant issue rooted in the lack of a shared understanding of PED, exacerbated by its more substantial integration into European rather than national incentives, and there is a notable strategic misalignment between the PED initiative and national/local legal, political, and financial systems. This positioning characterizes PED as complementary or supportive to cities' energy transition, rather than a primary objective. This dynamic may lead to other challenges, including insufficient commitment, a dearth of economic incentives, limited political and civic support or engagement, reluctance to invest, lack of motivation to gain knowledge about PEDs or participate, and a limited sense of collective effort and commitment. Consequently, individual personal or professional interests and knowledge emerge as the primary driving force for involvement. Moreover, our research highlights the prevailing uncertainties and ambiguities surrounding PED, both technically and non-technically, preventing many stakeholders

from making commitments.

Our research highlights the critical importance of clarity in the PED concept and recommends the need for a joint definition of PED and a roadmap, considering the contextual factors that influence cities, which may differ from one another. The contextual understanding is crucial for the replication of successful models and the development of a comprehensive roadmap for PEDs. Reflecting holistically on various aspects of PEDs through interviews, our research advocates for the definition of new roles and the clarification of existing ones to enhance the effectiveness and efficiency of PED implementation. This, we argue, is a fundamental step towards overcoming the challenges identified and realizing the full potential of PEDs in contributing to sustainable urban development.

Optimizing the decision-making process based on integrated urban models is recognized as a unique challenge by our research, requiring consideration of cultural, economic, and governmental factors. Addressing regulation becomes a significant challenge when administrative barriers, environmental agreements, and social factors are involved, highlighting the importance of avoiding preconceived solutions. Our inclusive approach emphasizes the engagement of stakeholders in the problem-definition phase, valuing their insights and perspectives to bridge the gap between solutions and stakeholder needs. Recognizing the innovative nature of PEDs, our study places a strong emphasis on the necessity for knowledge-sharing and collaborative efforts among stakeholders to establish effective implementation processes. We propose the development of a new partnership between public, private and people, emphasizing the need to explore enabling and inhibiting factors for actualizing it within multi-level governance systems.

Given that Salzburg and Stockholm scored better in governance than other cities, future studies can delve deeper into these cases to understand their governance mechanisms and identify success factors for effective governance. In aligning challenges in PED implementation with broader urban governance issues, our research advocates for role clarification and the creation of new roles within the governance structure. For instance, there is a need for the promotion of new roles and skills for facilitators within the complex governance systems, responsible for building trust, ensuring smooth communication, conflict management, and safeguarding win-win situations. They can facilitate the establishment of relationships with committed bureaucrats to ensure continuity and political support for PED initiatives and citizen engagement. Accordingly, our research suggests investigating which actors can play intermediary or facilitator roles and identifying the necessary characteristics or attributes (who can play that role, which sector is responsible and whys). A new education and training program is also proposed for different stakeholders to learn different aspects of PEDs as well as practical skills for co-creation and implementation of PEDs together.

6. Future research and perspectives

Regular evaluation and monitoring processes of both technical and non-technical aspects of PEDs, along with effective communication of outcomes, are advocated to foster transparency, collaboration, and shared responsibility for driving continuous improvement and quantifying Key Performance Indicators, enabling the replicability of success factors. Future research should assess the long-term impacts of PEDs on urban sustainability as a key aspect of future research. Such studies, according to our recommendation, would be invaluable in tracking the evolution of PEDs over time, evaluating their sustained performance against environmental, economic, and social benchmarks, and understanding their role in the adaptive resilience of urban infrastructures. Additionally, we emphasize the importance of extending the scope of research to include non-European contexts for a more comprehensive understanding. By examining PEDs in a range of international settings, researchers can gain a richer, more detailed understanding of how different regulatory frameworks, cultural nuances, and governance structures affect the development and success of PEDs, fostering a more inclusive and comprehensive dialogue on sustainable urban development.

Our research contends that by implementing these recommendations for inclusive decision-making processes and adopting adaptive problem-solving approaches, policymakers, urban planners, researchers, and other stakeholders involved in sustainable urban development and PED processes can significantly enhance the success and sustainability of their initiatives. Our study marks a critical juncture in understanding PEDs, offering lessons learned from various urban contexts that encompass integrated planning, community engagement, innovative financing models, technology integration, district-scale approaches, regulatory and policy support, flexible design, data-driven decision-making, knowledge transfer, social equity and inclusion, and measuring impact.

CRediT authorship contribution statement

Savis Gohari: Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **Soutullo Castro Silvia:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Touraj Ashrafian:** Writing – review & editing, Writing – original draft. **Thaleia Konstantinou:** Writing – review & editing, Writing – original draft, Conceptualization. **Emanuela Giancola:** Writing – review & editing, Writing – original draft. **Bahri Prebreza:** Writing – review & editing, Writing – original draft. **Laura Aelenei:** Writing – review & editing, Writing – original draft. **Lina Murauskaite:** Writing – review & editing, Writing – original draft. **Mingming Liu:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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