Journal of Sustainability for Energy
https://www.acadlore.com/journals/JSE

Fundamental Challenges in the Implementation of Positive Energy Districts: Definitions, Design, Technologies, and Sustainability

Emilio Sessa[1*], Lorenza Di Pilla[1], Roberta Rincione[1], Alberto Brunetti[1], Francesco Guarino[1], Maurizio Cellura[1, 2], Sonia Longo[1], Eleonora Riva Sanseverino[1]

[1] Department of Engineering, University of Palermo, 90128 Palermo, Italy
[2] Center for Sustainability and Ecological Transition, University of Palermo, 90100 Palermo, Italy

[*] Correspondence: Emilio Sessa (emilio.sessa@unipa.it)

Received: 10-03-2024 **Revised:** 11-06-2024 **Accepted:** 11-18-2024

Citation: E. Sessa, L. Di Pilla, R. Rincione, A. Brunetti, F. Guarino, M. Cellura, S. Longo, and E. R. Sanseverino, "Fundamental challenges in the implementation of Positive Energy Districts: Definitions, design, technologies, and sustainability," *J. Sustain. Energy*, vol. 3, no. 4, pp. 234–243, 2024. https://doi.org/10.56578/jse030403.

Abstract: Positive Energy Districts (PEDs) represent a crucial component of the energy transition and the development of climate-neutral urban environments. Given their significance, ongoing refinement in the definition and implementation of PEDs is essential. An in-depth analysis of the key characteristics of PEDs and the central role of stakeholders in their planning and modelling was presented in this study. The analysis encompasses five primary technological domains: energy efficiency, energy flexibility, e-mobility, soft mobility, and low-carbon generation. Both the enablers and barriers within a holistic framework, which integrates sustainability, as well as both tangible and intangible quality attributes, were identified. Key enabling factors, such as financial, social, innovation, and governance aspects, were examined to illustrate their impact on the successful implementation of PEDs. A co-creation process, highlighted as an essential outcome, contributes to a more refined understanding of the state of the art in PED design and implementation. In addition to the technical dimensions, the social, ecological, and cultural factors were shown to play a significant role, underscoring the importance of stakeholder engagement in achieving urban decarbonization. It can be concluded that a multidimensional approach, which incorporates not only technological innovations but also socio-ecological considerations, is necessary to effectively address the challenges inherent in the deployment of PEDs.

Keywords: PEDs; UBEM; PED design; PED implementation; Energy transition

1 Introduction

Occupying 2% of the worldwide land with a 50% of population living within their boundaries (expected to rise to the 68%) and considering the multi-sectoral activities insisting on the urban fabric [1, 2], cities are the main incubators to drive a change in the energy transition. In alignment with the 11th Sustainable Development Goal (SDG) of "making cities inclusive, safe, resilient, and sustainable" [3, 4], an overarching multidisciplinary approach is crucial, which must combine different dimensions, including housing, transport, information, and communication technology (ICT) systems as well as energy systems [5–7]. Starting from the definition of nearly/net/positive zero energy building up-scaled at the district level [8–11], district-scale energy systems could supply neighboring buildings, if there is a renewable energy surplus production, such as recharging electric vehicles [12–14].

In accordance with this, the definition of Positive Energy Blocks (PEBs) expands, following the European Innovation Partnership (EIP) on smart cities and community marketplace. The new definition of PEDs, as outlined in the European Union (EU) Commission's SET-Plan Action 3.2, "Smart Cities and Communities," is as follows: "A district with annual net zero energy import and net zero CO_2 emissions, working towards an annual local surplus production of renewable energy" [15].

Initially, the primary features of such districts were local energy efficiency, renewable energy supply, and energy flexibility in consumption. However, more recent developments have introduced additional dimensions, including inclusiveness, human-centricity, and resilience, as emphasized by the Joint Programming Initiative (JPI) Urban Europe. In this view, the district is being regarded as a community with cooperation and result sharing. All the people living in the district, households and owners share the net energy surplus, shifting seamlessly from consumers to producers, acquiring the status of prosumers.

The assimilation of this perspective has led to a new definition of PEDs. That is, PEDs are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas (GHG) 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 [16].

2 State of the Art on PEDs

The key topics that require attention to enhance understanding and foster greater awareness of the analysis presented in the literature are outlined below:

2.1 Definition

PEDs are complex systems focusing on energy use and generation, and, overall, on sustainability in inhabited areas, primarily urban and peri-urban areas, including rural or industrial areas. Despite general definitions being available, a widespread understanding of what constitutes a PED in connection to different climates and technical solutions has still to be addressed, including elements like energy balance and context factors. Archetypes and key design elements should be considered early on to guide PED development [17].

2.2 PED Design and Sustainability

Sustainable PED design requires a comprehensive approach that integrates technological, environmental, and socio-economic aspects [18]. Current assessment methods often isolate these factors, but PED targets demand a combined approach. Addressing these objectives from the early design stages ensures smoother progression without subsequent major revisions. PEDs pose challenges in integrating tools, stakeholder needs, and sustainable business models in both technical and non-technical aspects, creating an overarching vision and framework [19].

2.3 Technologies within PEDs

The building and mobility sectors play a key role in PEDs' decarbonization [20–23], but no universal technological strategy fits all contexts. PEDs must utilize a range of technologies to maximize renewable energy production, storage and supply, finding synergies with stakeholders and energy grids owners. However, the complexity of managing multiple energy systems increases with its up-scaling, requiring research-driven design solutions with the integration of more intelligent local distribution grids [24, 25].

2.4 Energy Modelling of PEDs

While research on energy modelling and performance optimization for districts has increased [26–32], there are still challenges with predicting accuracy and comparing results, especially for innovative components often found in PEDs and models used. The district scale introduces further complexities that differ from single-building analysis, requiring a variety of inputs and leading to issues with data availability and accuracy [33]. These include factors like human behaviour (occupancy), urban climate (micro-patterns), and energy systems (smart micro-grids). Additionally, uncertainties arise from various data sources, such as meteorological data and topology, while the lack of a standardized integration method complicates comparisons between models. Managing the large volume of data generated at the district level is another challenge to overcome, i.e., Building Information Modelling (BIM). Future research should focus on flexible modelling approaches that can adapt to different urban environments.

2.5 PEDs and Environment

Environmental impact assessment is crucial for PED sustainability, yet approaches vary in terms of boundaries and metrics [34]. A standardized, replicable, and transparent assessment framework is needed to evaluate environmental sustainability consistently at the district level. Recent efforts have focused on examining how PEDs impact the environment, using both outside-in and inside-out approaches. Although some protocols, such as the last GHG protocol by the World Resource Institute for Climate Neutral Cities or the traditional Life Cycle Assessment (LCA), applied at a district scale usually help to weight the impacts, the challenge lies in defining the boundaries of a PED. By taking the district as an autonomous entity, the positive and negative externalities of having a net-positive district in a fully urbanized context could be defined, which is a key point.

2.6 PEDs and Social Inclusiveness

Similarly to the previous point, by using an Environmental Social Governance (ESG) approach, the implementation of PEDs requires new frameworks to ensure social inclusivity and affordability for residents [35]. Social sustainability is crucial for well-being but is less established in PED assessment compared to other aspects. Key factors in sustainable urban development include access to local services, safety, sustainable transport, urban aesthetics, affordable housing, social participation, good environmental conditions, and job opportunities [36]. Within the context of PEDs, energy poverty emerges as a significant social issue [37]. Furthermore, the location of businesses within PEDs is increasingly seen as beneficial, as these entities may take advantage of the surplus of clean energy generated by the district. This, in turn, can have a positive impact on the scope 2 and scope 3 emissions of these companies. However, despite these factors, there is a need for a more structured quantitative framework to evaluate the social impacts and benefits of energy communities.

2.7 PED Economics and Governance

Developing PEDs and fostering energy communities introduce new business models and governance systems related to energy networks, mobility, and buildings. Challenges include managing costs, energy trade-offs, and governance structures. These issues require further exploration to ensure stakeholder engagement and successful implementation.

2.8 Stakeholder Engagement

One of the key challenges in implementing PEDs is stakeholder engagement during the planning and implementation phases [38]. This is caused by the wide range of involved parties, including municipal agencies, energy contractors, real estate companies, local business owners, and residents, many of whom may not have collaborated previously. As complexity increases, effective stakeholders' engagement becomes crucial [39]. A deeper understanding of stakeholders' dynamics and systematic mapping can improve engagement and project success. The gap between technical issues and social interactions poses a challenge to widespread PED adoption for decarbonizing the built environment. The concept of co-creation, which fosters innovation outside traditional research institutions and involves all stakeholders, is essential in addressing these challenges.

3 Core PED Challenges

The challenges associated with PEDs and the areas that require further attention to enhance understanding of stakeholder engagement can be categorized into the following thematic areas:

(a) PED definitions and fundamentals;
(b) Quality-of-life indicators in PEDs;
(c) Technologies in PEDs: development, use and barriers;
(d) PED modelling: further needed to model PEDs;
(e) Sustainability assessment of PEDs;
(f) Stakeholder engagement within the design process.

3.1 PED Definitions and Fundamentals

To validate the definitions proposed in the literature, it is important to consider some aspects of PEDs. Compared to other aspects, some aspects were considered more strategical in this study, i.e., statistics, approach to technology, inhabitants' well-being, and social inclusiveness.

To involve citizens and decision-makers in this process is another influencing factor, giving them clear signals, such as key performance indicators (KPIs), to interpret the feasibility and planning of every single PED case. There are many challenging points related to the interpretation of PEDs as they are defined.

The technological aspect is certainly one of these improvement points in terms of implementation, but it is not the only one. For instance, data harvesting and effective modelling are fundamental to design and plan PED realization. Therefore, data quality and collection are critical when defining a PED or planning on future scenarios. The existing definitions of PEDs, as outlined in the scientific and technical literature, may need to be revised. In particular, the cut-off threshold for defining a PED should be reconsidered. The current threshold, which may define PEDs as those districts with only a slight energy surplus (a few kilowatts beyond their energy need), might not fully capture the complexities of real-world scenarios.

3.2 Quality-of-Life Indicators in PEDs

With their very distinctive practical functions, PEDs have a clear impact on people's lifestyle and quality of life. However, the definition of benefit itself is all but simple and difficult to harness because it should consider not merely the energy surplus and the economic advantage, but even less tangible aspects.

To define these benefits, it is necessary to define additional attributes. The two classes of indicators were defined as follows:

(a) "Tangible" quality categories consist of indoor and outdoor environmental features that are physically measurable (e.g., temperature, air-quality, noise and local climate, including safety and security): the level of accessibility to services like transport facility, including walkability, energy services and sustainable waste management; the access to amenities like education, sports, culture provisions for children (i.e., gardens); the aesthetic quality; citizen engagement; access to greenery and information flow;

(b) "Intangible" quality categories consist of a set of non-measurable features such as well-being, quality and social connection, level of self-esteem and more.

Additional efforts are needed to understand if the "intangible" categories should be better assessed by setting up a governance model to deliver an operational result comprising stakeholders as part of the decision-making process. This approach is shared and familiar to all stakeholders and creates an easy-to-navigate environment and a useful tool to assist decision-making processes.

3.3 Technologies in PEDs: Development, Use and Barriers

Four main groups of technologies were identified, as shown in Table 1. Each of these technology categories has the potential to address specific challenges in the management and implementation of PEDs.

Table 1. Summary of the main technologies supporting the PED implementation

Technology Area	**Description**	**Key Features/Tools**
Energy efficiency	Reduces emissions and energy waste in terms of LCA through advanced systems.	• Carbon Capture and Storage (CCS) • Circular systems • Energy-saving technologies • Smart microgrids
Energy flexibility	Balances energy demand and production through smart and automated systems.	• Artificial Intelligence (AI) integration • Machine learning, blockchain, and 5G • Sensor-driven energy management • Electric vehicles and charging stations
E-mobility and soft mobility	Promotes clean transportation and sustainable commuting.	• Low-emission public transport • Shared mobility solutions (e.g., car-sharing, bike-sharing) • Photovoltaic (PV) systems
Low-carbon energy generation	Focuses on renewable energy sources and green energy production technologies.	• On-site energy generation facilities • Renewable energy integration challenges • Micro-scale wind power

The continual improvement of energy-efficient technologies constitutes the founding stone of emissions reductions (i.e., to be supported by CCS as natural-based solutions/technologies, or circular approach). The impact of these technological choices is related to important investments in in changes of strategy and priorities in the planning and retrofitting of PEDs or entire urban districts.

Automation, smart grids and sensor-driven living spaces are at the core of this second challenge to overcome. Energy flexibility would be sufficed by an adequate degree of control, switching and facilitating the interplay between energy demand and production. With the intervention of AI, smart microgrids will be the key to better energy management in PED organization. This dimension involves the development and implementation of software and hardware technologies (like machine learning, blockchain, 5G, city management platforms, digital twins and like measuring controls, long-term/short-term storage) and is perceived by stakeholders as the enabler of quasi-fully automated building and clusters of buildings (districts). Therefore, it is pivotal.

The urban fabric accommodates commuters and residents, making mobility—including both public and private modes—a critical component of urban planning. Particular emphasis is placed on e-mobility and "soft mobility," which incorporates shared vehicles and lifestyle changes. In fact, the emissions related to this sphere are partially avoidable and reduceable with public low-emission transportation vehicles. However, there can be more improvement with the incentivization of similar measures like the ownership of electric vehicles and a capillary electrification for the charging stations.

Finally, the low-carbon generation technologies, like the PV fields, pose the challenge to find available space to physically build the on-site facilities. All these areas contribute to supporting PEDs in meeting their positive energy balance, while limiting the energy demand, granting flexible options, guaranteeing the management of energy demand and production, optimizing the mobility sector with electrification and car sharing, and reducing carbon generation within the PED boundaries.

In general, by considering the previous points about the technological side of PEDs, related challenges were summarized into the following types:

(a) Capacity building and policy issues: Maintaining a good knowledge transfer among the public, the administrators, and city-level operators is essential for the success of a PED. Clear regulation is needed to classify the PEDs based on some criteria, and involving policy-makers to secure adequate funding can be supportive in this specific issue.

(b) Social challenges and considerations: Cultural barriers, including heritage preservation, with affordability and accessibility to new energy solutions for all small community members, need to be addressed too. Following the principle of "leaving no one behind," the effort should be the one to avoid excluding certain populations. Knowledge exchange among producers, operators and users should be facilitated to support trust building and social inclusion among stakeholders.

(c) Financial barriers: The upfront investment can be considered a real financial constraint and the insufficient funds to realize PED projects may remain out of reach. Therefore, it deserves a peculiar and managerial approach to allocate funds and resources.

(d) Data management: Data standardization is vital for the realization of a PED project because it ensures compatibility and interoperability among systems and stakeholders, facilitating seamless integration. In governing data sharing, data privacy plays a significant role. In fact, it consists of the interplay between making data accessible for research and development and safeguarding privacy rights.

(e) Developing sustainable business models and ownership structures: It ensures the long-term availability of the PED project. New grid management approaches like the smart grid remove the dependence of storage, often critical to design. In addition to this, the digital technology involved in PED management could work as an additional implementation resistance because individuals or communities are less familiar with it.

3.4 PED Energy Modelling

The modelling of energy systems within PEDs involves a dynamic process, encompassing three primary phases: planning, design, and operation. Each step pertains to a specific set of enablers and barriers. After the implementation of each step, feedback with correcting actions would restart the loop.

The development of various tools for modelling PEDs can help decision-makers in design and planning. However, there is a lack of accessible, open-source modelling tools with clear instructions. For example, both academia and decision-makers express the need for an inclusive and user-friendly resource that explains each PED model's application. In the context of Urban Building Energy Modelling (UBEM) [26] (the process of simulating and analyzing the energy performance of buildings at the urban scale rather than focusing on a single building), many studies have analyzed existing tools, such as renewable energy systems and demand-side management models. However, the most critical point remains the data availability.

In this view, BIM, which is sparking much interest among across diverse sectors, would contribute to mitigate the negative impact, due to the impact of lack of real data on the outcome and related interpretation and planning of these models. In fact, it is possible to state, based on real-case scenarios and analysis, that the absence of a fully automated framework for UBEM makes the top-to-toe process complex and time-consuming, especially for non-experts. The reason is that much work is still done manually. Another issue includes a narrow focus on technical aspects, often overlooking socio-political factors. A more comprehensive modelling approach that includes social, ecological, and cultural considerations is needed in supporting decision-makers and accelerate the energy transition.

3.5 Sustainability Assessment of PEDs

Implementing PEDs involves both financial costs and potential revenues, along with several key factors to consider in the organizational and business models. Considering the structure of tangible and intangible quality-of-life indicators, financial terminology comes to aid and highlights the investment perspective that a PED has.

As for costs, firstly, the initial investment for shared energy systems, like solar panels and storage, can be significant, especially when scaling from individual buildings to entire districts. Secondly, there is also a risk associated with shared technologies. While they promise lower energy bills, they introduce uncertainties around cost-sharing and long-term benefits. Moreover, business models for PEDs are highly site-specific, meaning that the costs can vary depending on the location and local urban characteristics.

As for revenues, PEDs can generate savings by lowering energy bills for users, due to shared energy production. There are also financial incentives and climate-related benefits, such as subsidies or tax breaks, which can make these projects more economically feasible and sustainable. Additionally, PEDs often enhance property values due to the improved energy efficiency and sustainable infrastructure they bring to the area.

The following are the key aspects for business models:

(a) District size and scalability: Unlike single buildings, costs for districts do not increase in a straightforward way with the number of buildings. The business models need to reflect the complexity of scaling up to entire districts rather than simply applying building-level solutions.

(b) Site-specific business models: Since PED models are highly tailored to local contexts, what works in one area might not work in another. This means business models need to be flexible and adaptable to specific urban settings.

(c) Shared systems and management: While sharing energy systems can reduce costs, it also comes with investment risks. To ensure fairness and prevent disparities in energy market participation, stakeholders have suggested that a non-profit entity could manage the PED. This would help maintain transparency and control over shared resources.

(d) Incorporating social aspects: One of the most challenging yet important aspects of PEDs is incorporating social factors like job creation, community engagement, and public space improvements into the business model. These benefits are harder to quantify but critical for long-term sustainability. This requires translating some of these qualitative benefits into measurable economic terms.

(e) Environmental impact: Quantifiable environmental benefits, such as reduced emissions and increased green spaces, are feasible to be included in financial models. However, harder-to-measure impacts, such as health improvements or the preservation of cultural heritage, still need to be accounted for and thoughtfully integrated.

The sustainability domain naturally gives importance to energy aspects or efficiency and social implications of living in a PED in terms of relevance. The two options shown are complimentary and convergent. In fact, PEDs may be beneficial to overcome the dualism between energy and social issues, such as ensuring fair access to energy for all citizens and mitigating energy poverty. In addition, it has been agreed that when aiming at targeting sustainability, setting realistic targets on a roadmap could be the key. PEDs can offer a widespread set of different technology options, but occupants, workers and all the stakeholders involved in the PED design should be prone to change with the implied modification of habits and routines.

3.6 Stakeholder Engagement within the Design Process

PED studies offer significant benefits to a wide range of stakeholders. Citizens, including disadvantaged groups, can integrate energy-efficient and sustainable solutions into their daily lives, fostering a culture of clean energy. Local communities benefit from improved living standards, while local authorities, policy-makers, and urban planners use insights from PED research to make informed decisions on urban development, energy policies, and sustainability initiatives. Scientists and researchers leverage data from PED studies to push the boundaries of knowledge, innovate methodologies, and conduct detailed meta-analyses of energy systems. Furthermore, educational institutions play a crucial role by translating complex findings into simpler concepts, making clean energy accessible to students and the public, thereby raising awareness of sustainability from an early age. Collectively, PED studies drive collaboration and knowledge dissemination, advancing the energy transition and fostering sustainable development.

Private companies, including technology developers, start-ups, and energy providers, can leverage insights from PED research to innovate and refine their products, services, and infrastructure. They can use these findings to support local development projects and advance smart urban technologies. Non-Governmental Organizations (NGOs) and civil society groups also benefit by accessing data that helps them advocate for sustainable solutions.

Finally, even if it is not a typical stakeholder, the environment is a key beneficiary of PED implementation. PEDs contribute to cleaner, more sustainable urban ecosystems and support the global transition to renewable energy, with potential applications in both developed and developing countries.

Stakeholders in the sustainable development of PEDs include not only the obvious groups like residents and municipalities but also "hidden" stakeholders such as building owners, local investors, real estate developers, employers, and customers. Their diverse interests, ranging from energy tariffs to greener public spaces, influence the PED design process. Engaging all the subjects of interest requires targeted communication to clearly convey the environmental, economic, and social benefits of PED participation. For real estate developers, highlighting market value through certifications, and for industries, emphasizing competitiveness can encourage involvement. Younger generations, more receptive to sustainability, should be engaged through storytelling and social media to spread their awareness of PED benefits.

In the conceptual map in Figure 1, the main takeaways are conceptualized. They are divided into what the implementation of a PED "must address," "require," "include," "must consider," and "should include" based on this study and the related consequences, reasons or purposes.

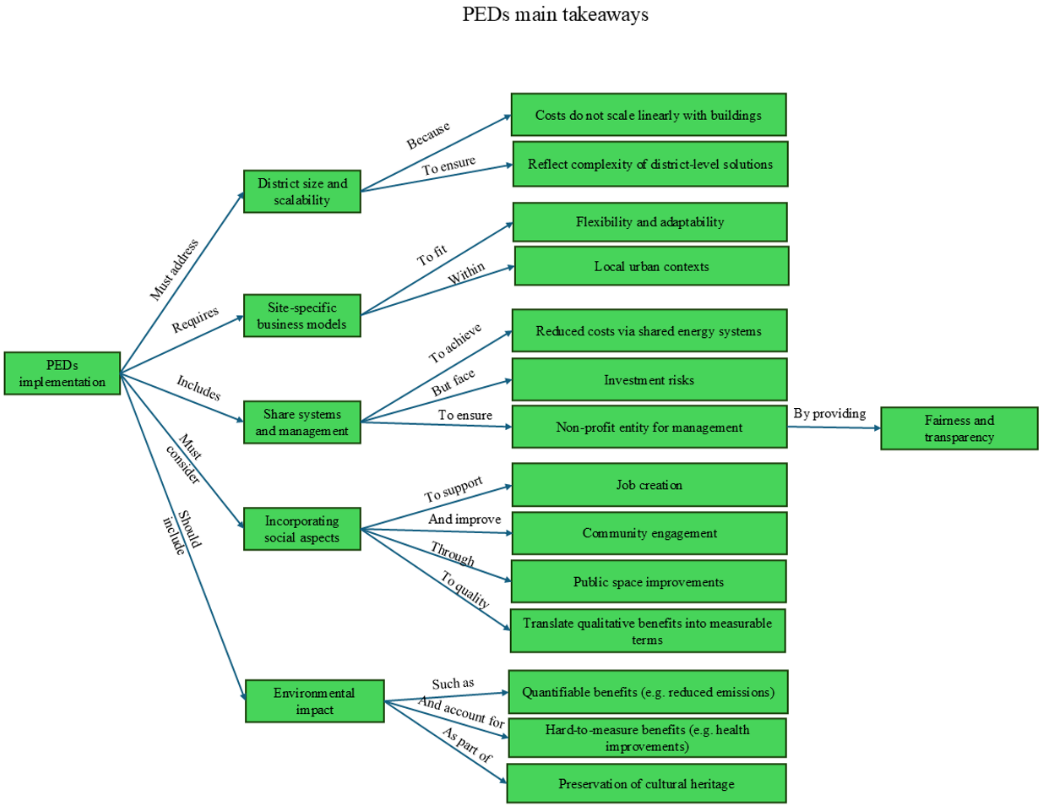

Figure 1. Main takeaways conceptualized in a map

4 Conclusions

On the road to implement PEDs, there are some key factors needing attention such as defining PED characteristics (morphological, socio-economic, and technological), addressing business models, and overcoming barriers like social acceptance and lack of standardization. The last two points need a deeper understanding and consistency in literature and real-case scenarios. Along with the integration of quality-of-life, indicators like comfort, security and technology are also highlighted as crucial in the role of PEDs.

Learning from real-life PED implementations with data-driven approaches (e.g., digital twins - virtual replicas of real-world buildings and their associated systems) within an urban environment, or BIM (the process of creating a computer-based representation of a building's energy use) are at the basis of more standardized guidelines that can drive policy and planning. In addition to these priorities, integrating sustainability, fostering social inclusion, and developing innovative business models for market integration can also support planning and evaluation.

The main key findings can be summarized as follows:

- PED characteristics, defining PED attributes (morphological, socio-economic, technological), can help standardize and compare different districts, promoting transparency, comparison with other cases and the scenario-based planning. The lack of standardized and data collecting frameworks like BIM is a major weakness point among the others;

- Business models are critical for ensuring long-term viability and attracting investments. However, they need to be better embedded in the actual PED frameworks, with a bigger harmonized effort to approach every project with a similar (or more than one) strategy of evaluation and feasibility. The lack of actual standardization, regulatory support, social acceptance, and investment allocation work as potential barriers against seamless PED implementation. Renewable Energy Communities (RECs), working as physically boundaryless entities on the territory, contribute to energy sharing and function as trailblazers to the recognition of PEDs and synergic planning;
- Key technologies, including renewable energy, energy flexibility, and sustainable mobility, combined with financing instruments and innovative governance, are only one instrument to overcome challenges and solve such a complex topic of PEDs. Other important quality-of-life indicators like comfort, security, and affordability play an important role into PED designs, reflecting that the values of sustainability, inclusivity, well-being, social inclusion and education are dimensions that influence a successful designing process of PEDs;
- UBEM, BIM and digital twins have the potential to enhance real-time monitoring, control, and optimization of PEDs, offering insights into energy systems and improving project modification and ad-hoc interventions.

In conclusion, research and development should focus on data integration, UBEM standardization, stakeholder collaboration, innovative business models and innovative technologies to drive PED adoption and sustainability.

Author Contributions

Conceptualization, E. Sessa, F. Guarino, M. Cellura, E. R. Sanseverino; methodology, E. Sessa, L. Di Pilla; validation, E. Riva Sanseverino, E. Sessa, F. Guarino, R. Rincione; formal analysis, E. Sessa, M. Cellura, L. Di Pilla, A. Brunetti; investigation, E. Sessa, A. Brunetti. L. Di Pilla; resources, E. Sessa, F. Guarino, A. Brunetti; data curation, E. Sessa, L. Di Pilla, M. Cellura; writing—original draft preparation, E. Sessa; writing—review and editing, E. Sessa, F. Guarino, M. Cellura, E. Riva Sanseverino; visualization, E. Sessa, L. Di Pilla, R. Rincione, C.R. and M.S.; supervision, F. Guarino, E. R. Sanseverino, M. Cellura. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the Italian Government MUR Grant No.: P2022LLYAF – PRIN 2022 PNRR "NETPLUS: Neighborhood Energy Transition: towards Positive energy balance and carbon neutral districts", Funded by European Union – Next Generation EU, CUP: B53D23027120001.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] United Nations, "68% of the world population projected to live in urban areas by 2050, says UN," 2018. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

[2] Z. Fatima, T. Vacha, K. Swamygowda, and R. Qubailat, "Getting started with Positive Energy Districts: Experience until now from Maia, Reykjavik, Kifissia, Kladno and Lviv," *Sustainability*, vol. 14, no. 10, p. 5799, 2022. https://doi.org/10.3390/su14105799

[3] United Nations, "Make cities and human settlements inclusive, safe, resilient and sustainable." https://sdgs.un.org/goals/goal11

[4] M. Shahmohammad, M. M. Salamattalab, W. Sohn, M. Kouhizadeh, and N. Aghamohmmadi, "Opportunities and obstacles of blockchain use in pursuit of sustainable development goal 11: A systematic scoping review," *Sustain. Cities Soc.*, vol. 112, p. 105620, 2024. https://doi.org/10.1016/j.scs.2024.105620

[5] F. Koch and S. Ahmad, "How to measure progress towards an inclusive, safe, resilient and sustainable city? Reflections on applying the indicators of sustainable development goal 11 in Germany and India," in *Urban Transformations: Sustainable Urban Development Through Resource Efficiency, Quality of Life and Resilience*. Springer, 2018, pp. 77–90. https://doi.org/10.1007/978-3-319-59324-1_5

[6] H. Sarvari, A. Mehrabi, D. W. Chan, and M. Cristofaro, "Evaluating urban housing development patterns in developing countries: Case study of Worn-out Urban Fabrics in Iran," *Sustain. Cities Soc.*, vol. 70, p. 102941, 2021. https://doi.org/10.1016/j.scs.2021.102941

[7] M. Gondeck, M. A. Triebel, A. Steingrube, V. Albert-Seifried, and G. Stryi-Hipp, "Recommendations for a positive energy district framework – Application and evaluation of different energetic assessment methodologies," *Smart Energy*, vol. 15, p. 100147, 2024. https://doi.org/10.1016/j.segy.2024.100147

[8] E. Derkenbaeva, S. H. Vega, G. J. Hofstede, and E. Van Leeuwen, "Positive energy districts: Mainstreaming energy transition in urban areas," *Renew. Sustain. Energy Rev.*, vol. 153, p. 111782, 2022. https://doi.org/10.1016/j.rser.2021.111782

[9] A. Bruck, S. D. Ruano, and H. Auer, "One piece of the puzzle towards 100 Positive Energy Districts (PEDs) across Europe by 2025: An open-source approach to unveil favourable locations of PV-based PEDs from a techno-economic perspective," *Energy*, vol. 254, p. 124152, 2022. https://doi.org/10.1016/j.energy.2022.124152

[10] H. Vandevyvere, D. Ahlers, and A. Wyckmans, "The sense and non-sense of PEDs—Feeding back practical experiences of positive energy district demonstrators into the European PED framework definition development process," *Energies*, vol. 15, no. 12, p. 4491, 2022. https://doi.org/10.3390/en15124491

[11] J. Natanian, F. Guarino, N. Manapragada, A. Magyari, E. Naboni, F. De Luca, S. Cellura, A. Brunetti, and A. Reith, "Ten questions on tools and methods for positive energy districts," *Build. Environ.*, vol. 255, p. 111429, 2024. https://doi.org/10.1016/j.buildenv.2024.111429

[12] S. Sareen, V. Albert-Seifried, L. Aelenei, F. Reda *et al.*, "Ten questions concerning positive energy districts," *Build. Environ.*, vol. 216, p. 109017, 2022. https://doi.org/10.1016/j.buildenv.2022.109017

[13] D. Mihailova, I. Schubert, P. Burger, and M. M. C. Fritz, "Exploring modes of sustainable value co-creation in renewable energy communities," *J. Clean. Prod.*, vol. 330, p. 129917, 2022. https://doi.org/10.1016/j.jclepro.2021.129917

[14] D. Mihailova, I. Schubert, A. L. Martinez-Cruz, A. X. Hearn, and A. Sohre, "Preferences for configurations of Positive Energy Districts – Insights from a discrete choice experiment on Swiss households," *Energy Policy*, vol. 163, p. 112824, 2022. https://doi.org/10.1016/j.enpol.2022.112824

[15] SET-Plan Working Group, "Europe to become a global role model in integrated, innovative solutions for the planning, deployment, and replication of Positive Energy Districts," in *SET-Plan Action*, vol. 32, 2018, pp. 1–72.

[16] Urban Europe, *White Paper on PED reference framework for Positive Energy Districts and Neighbourhoods*, 2020. White-Paper-PED-Framework-Definition-2020323-final.pdf

[17] A. Gabaldón Moreno, F. Vélez, B. Alpagut, P. Hernández, and C. Sanz Montalvillo, "How to achieve Positive Energy Districts for sustainable cities: A proposed calculation methodology," *Sustainability*, vol. 13, no. 2, p. 710, 2021. https://doi.org/10.3390/su13020710

[18] R. Aghamolaei, M. H. Shamsi, M. Tahsildoost, and J. O'Donnell, "Review of district-scale energy performance analysis: Outlooks towards holistic urban frameworks," *Sustain. Cities Soc.*, vol. 41, pp. 252–264, 2018. https://doi.org/10.1016/j.scs.2018.05.048

[19] L. Bottecchia, A. Gabaldón, T. Castillo-Calzadilla, S. Soutullo, S. Ranjbar, and U. Eicker, "Fundamentals of energy modelling for positive energy districts," *Sustain. Energy Build.*, pp. 435–445, 2022. https://doi.org/10.1007/978-981-16-6269-0_37

[20] S. F. Zhang, M. Ma, N. Zhou, J. Y. Yan, W. Feng, R. Yan, K. R. You, J. J. Zhang, and J. Ke, "Estimation of global building stocks by 2070: Unlocking renovation potential," *Nexus*, vol. 1, no. 3, p. 100019, 2024. https://doi.org/10.1016/j.ynexs.2024.100019

[21] X. W. Xiang, N. Zhou, M. Ma, W. Feng, and R. Yan, "Global transition of operational carbon in residential buildings since the millennium," *Adv. Appl. Energy*, vol. 11, p. 100145, 2023. https://doi.org/10.1016/j.adapen.2023.100145

[22] R. Yan, M. Ma, N. Zhou, W. Feng, X. W. Xiang, and C. Mao, "Towards COP27: Decarbonization patterns of residential building in China and India," *Appl. Energy*, vol. 352, p. 122003, 2023. https://doi.org/10.1016/j.apenergy.2023.122003

[23] H. Yuan, M. Ma, N. Zhou, H. Xie, Z. Ma, X. Xiang, and X. Ma, "Battery electric vehicle charging in China: Energy demand and emissions trends in the 2020s," *Appl. Energy*, vol. 365, p. 123153, 2024. https://doi.org/10.1016/j.apenergy.2024.123153

[24] E. Marrasso, C. Martone, G. Pallotta, C. Roselli, and M. Sasso, "Assessment of energy systems configurations in mixed-use Positive Energy Districts through novel indicators for energy and environmental analysis," *Appl. Energy*, vol. 368, p. 123374, 2024. https://doi.org/10.1016/j.apenergy.2024.123374

[25] A. Bruck, S. Díaz Ruano, and H. Auer, "A critical perspective on positive energy districts in climatically favoured regions: An open-source modelling approach disclosing implications and possibilities," *Energies*, vol. 14, no. 16, p. 4864, 2021. https://doi.org/10.3390/en14164864

[26] U. Ali, M. H. Shamsi, C. Hoare, E. Mangina, and J. O'Donnell, "Review of urban building energy modeling

(UBEM) approaches, methods and tools using qualitative and quantitative analysis," *Energy Build.*, vol. 246, p. 111073, 2021. https://doi.org/10.1016/j.enbuild.2021.111073

[27] A. Brunetti, S. Cellura, F. Guarino, S. Longo, M. Mistretta, F. Reda, and R. Rincione, "Development of an early design tool for the sustainability assessment of positive energy districts: Methodology, implementation and case-studies," *J. Phys.: Conf. Ser.*, vol. 2600, no. 8, p. 82020, 2023. https://doi.org/10.1088/1742-6596/2600/8/082020

[28] T. H. Trulsrud and J. van der Leer, "Towards a positive energy balance: A comparative analysis of the planning and design of four positive energy districts and neighbourhoods in Norway and Sweden," *Energy Build.*, vol. 318, p. 114429, 2024. https://doi.org/10.1016/j.enbuild.2024.114429

[29] F. Guasselli, A. Vavouris, L. Stankovic, V. Stankovic, S. Didierjean, and K. Gram-Hanssen, "Smart energy technologies for the collective: Time-shifting, demand reduction and household practices in a Positive Energy Neighbourhood in Norway," *Energy Res. Soc. Sci.*, vol. 110, p. 103436, 2024. https://doi.org/10.1016/j.erss.2024.103436

[30] I. Aparisi-Cerdá, D. Ribó-Pérez, T. Gómez-Navarro, M. García-Melón, and J. Peris-Blanes, "Prioritising Positive Energy Districts to achieve carbon neutral cities: Delphi-DANP approach," *Renew. Sustainable Energy Rev.*, vol. 203, p. 114764, 2024. https://doi.org/10.1016/j.rser.2024.114764

[31] T. Castillo-Calzadilla, R. Garay-Martinez, and C. M. Andonegui, "Holistic fuzzy logic methodology to assess positive energy district (PathPED)," *Sustain. Cities Soc.*, vol. 89, p. 104375, 2023. https://doi.org/10.1016/j.scs.2022.104375

[32] E. Derkenbaeva, G. J. Hofstede, E. van Leeuwen, S. H. Vega, and J. Wolfers, "ENERGY Pro: Spatially explicit agent-based model on achieving Positive Energy Districts," *MethodsX*, vol. 12, p. 102779, 2024. https://doi.org/10.1016/j.mex.2024.102779

[33] U. Eicker, "Introduction: The challenges of the urban energy transition," in *Urban Energy Systems for Low-Carbon Cities*, 2019, pp. 1–15.

[34] F. Guarino, A. Bisello, D. Frieden, J. Bastos *et al.*, "State of the art on sustainability assessment of Positive Energy Districts: Methodologies, indicators and future perspectives," *Sustain. Energy Build.*, pp. 479–492, 2021. https://doi.org/10.1007/978-981-16-6269-0_40

[35] A. X. Hearn, A. Sohre, and P. Burger, "Innovative but unjust? Analysing the opportunities and justice issues within positive energy districts in Europe," *Energy Res. Soc. Sci.*, vol. 78, p. 102127, 2021. https://doi.org/10.1016/j.erss.2021.102127

[36] H. Haarstad and M. W. Wathne, "Are smart city projects catalyzing urban energy sustainability?" *Energy Policy*, vol. 129, pp. 918–925, 2019. https://doi.org/10.1016/j.enpol.2019.03.001

[37] J. P. Gouveia, J. Seixas, P. Palma, H. Duarte, H. Luz, and G. B. Cavadini, "Positive energy district: A model for historic districts to address energy poverty," *Front. Sustain. Cities*, vol. 3, p. 648473, 2021. https://doi.org/10.3389/frsc.2021.648473

[38] S. Bossi, C. Gollner, and S. Theierling, "Towards 100 Positive Energy Districts in Europe: Preliminary data analysis of 61 European cases," *Energies*, vol. 13, no. 22, p. 6083, 2020. https://doi.org/10.3390/en13226083

[39] J. A. Rankinen, S. Lakkala, H. Haapasalo, and S. Hirvonen-Kantola, "Stakeholder management in PED projects: Challenges and management model," *Int. J. Sustain. Energy Plan. Manag.*, vol. 34, pp. 91–106, 2022. https://doi.org/10.54337/ijsepm.6979