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Positive Energy Districts: Fundamentals, Assessment Methodologies, Modeling and Research Gaps

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Abstract: The definition, characterization and implementation of Positive Energy Districts is crucial in the path towards urban decarbonization and energy transition. However, several issues still must be addressed: the need for a clear and comprehensive definition, and the settlement of a consistent design approach for Positive Energy Districts. As emerged throughout the workshop held during the fourth edition of Smart and Sustainable Planning for Cities and Regions Conference (SSPCR 2022) in Bolzano (Italy), further critical points are also linked to the planning, modeling and assessment steps, besides sustainability aspects and stakeholders' involvement. The "World Café" methodology adopted during the workshop allowed for simple—but also effective and flexible—group discussions focused on the detection of key PED characteristics, such as morphologic, socio-economic, demographic, technological, quality-of-life and feasibility factors. Four main work groups were defined in order to allow them to share, compare and discuss around five main PED-related topics: energy efficiency, energy flexibility, e-mobility, soft mobility, and low-carbon generation. Indeed, to properly deal with PED challenges and crucial aspects, it is necessary to combine and balance these technologies with enabler factors like financing instruments, social innovation and involvement, innovative governance and far-sighted policies. This paper proposes, in a structured form, the main outcomes of the co-creation approach developed during the workshop. The importance of implementing a holistic approach was highlighted: it requires a systematic and consistent integration of economic,

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environmental and social aspects directly connected to an interdisciplinary cross-sectorial collaboration between researchers, policymakers, industries, municipalities, and citizens. Furthermore, it was reaffirmed that, to make informed and reasoned decisions throughout an effective PED design and planning process, social, ecological, and cultural factors (besides merely technical aspects) play a crucial role. Thanks to the valuable insights and recommendations gathered from the workshop participants, a conscious awareness of key issues in PED design and implementation emerged, and the fundamental role of stakeholders in the PED development path was confirmed.

Keywords: positive energy districts; world café method; stakeholder engagement; PED design; PED implementation

1. Introduction

The energy transition and the decarbonization of the energy sector are key aspects of the transformation that societies will have to face in the coming decades. In this context, cities can drive the energy transition in several sectors, such as energy, transport, construction, industry, and agriculture [1]. In fact, while cities occupy only 2% of the total land, 50% of the world's population currently lives in urban areas, and this is expected to increase to 68% by 2050 [2,3]. Moreover, they include different activity types, such as residential, commercial, and industrial, that contribute to 70% of greenhouse gas emissions and about two-thirds of the global energy demand [4,5]. The key role of cities in the ongoing energy transition is also highlighted in Sustainable Development Goal 11, which aims to "make cities inclusive, safe, resilient and sustainable" [6–9]. The transformation of the building stock, mobility systems, industries and urban infrastructures will require an integrated and multidisciplinary approach at different levels, including housing, transport, information and communication technology (ICT) systems, and energy systems [10–13]. This transformation must ensure environmental, economic, and social sustainability for both current and future generations. In this framework, Positive Energy Districts (PEDs) will play a key role in the coming years, as a necessary step towards the scaling up of the decarbonization process [9].

The PED concept was developed from previous ideas, such as Nearly/Net/Positive Zero Energy Buildings, extending them from the single building to the district scale, in order to exploit the energy mutuality between buildings and urban decarbonization [14–17]. The need to broaden the perspective arises from several key aspects of improvements over a single building approach [16,18,19]. For example, district approaches could offer benefits both in terms of energy system design and integration, and in terms of striving towards optimized urban morphology. District-scale energy systems could offer economical and technical scale benefits (compared to the mere overlay of building energy systems) by exploiting local energy exchanges between different buildings, providing electric mobility applications from excess of renewable energy generation, and providing energy storage systems at the district scale. In addition, PEDs could offer an opportunity to accomplish the directive on renewable energy communities, as they can facilitate the involvement in energy systems to a broad swathe of locally based stakeholders [20–22].

Since 2015 and based on the outcomes of the EU FP7 EeB-generation project Next-Buildings, the concept of a "Positive Energy Block" (PEB) has been coined for adoption by the European Innovation Partnership on Smart Cities and Communities Marketplace (currently Smart Cities Marketplace) [18]. Expanding on this initiative, a modified concept of a "Positive Energy District" (PED) was subsequently defined by the European Commission in the SET-Plan Action 3.2 "Smart Cities and Communities" in 2018 as "a district with annual net zero energy import and net zero CO_2 emissions, working towards an annual local surplus production of renewable energy" [23]. Beyond the energy and emission balance requirements, this definition clearly stresses the three key features of a PED: energy efficiency, local renewable energy supply, and energy flexibility consumption [19]. Subsequently, the Joint Programming Initiative (JPI) Urban Europe extended this definition considering inclusiveness, human-centricity, and resilience to the distribution grid [24]. The most widely acknowledged definition is, in fact: "Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability." [24]. This definition includes a more specific focus on energy use sectors and infrastructures and on the pivotal role of the interaction between buildings, including peer-to-peer solutions and energy communities. The importance of not only achieving countable and mathematical targets but also ensuring a "good life" for all occupants (while being in line with sustainability aspects) is significantly stressed as well.

Furthermore, in 2018, the European Commission formally introduced PEB and PED-related requirements to the Horizon 2020 project calls on Smart Cities and Communities Lighthouse projects, based on a slightly different definition [24].

As a result, several EU-funded projects, such as "ATELIER" [25], "Smart- BEEjS" [26], "MAKING CITY" [27], "CityxChange" [28] or "SPARCS" [29], are carrying out research and development activities on Positive Energy Districts, increasing the scientific interest around this concept.

In this context, the International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Annex 83 "Positive Energy Districts" has started to carry out further research on PED stakeholders' involvement, definition refinement, the identification of technical solutions, and the creation of modeling tools, as well as on the PED sustainability impact assessment [30]. Moreover, Annex 83 has broadened the scope from a European to an international perspective.

State of the Art on Positive Energy Districts

Under these premises, Positive Energy Districts could potentially be among the solutions paving the way for a true decarbonization of the urban environment. However, several issues need to be investigated at different levels, mirroring the points mentioned in the definition: technical, design, energy and mathematical modeling, sustainability, the definition itself, and stakeholders' involvement. Several knowledge gaps can be clearly traced in the domain of Positive Energy Districts, which range from the clear and univocal determination of a PED definition to the lack of a standardized sustainability framework for the assessments of PEDs, the most suitable allocation of technologies to achieve a PED in different climates, the use of the most appropriate energy modeling/digital-twin techniques for PEDs, and the need for refining substantially business models and governance models for PED applications. The core issues related to these points will be briefly addressed. The aim of this literature analysis is to frame the context for the analysis of the core contents of the paper from the World Café exercise. A brief synthesis of the main open issues connected to PEDs is provided below.

PED Definition. Positive Energy Districts are complex systems that focus on the management of both energy use and generation, as well as on the general sustainability of inhabited areas (so far, most examples have focused on urban areas, but "rural" or "peri-urban" PEDs are not excluded in principle). However, although various definitions of PEDs have been provided, these are very general and rarely fully inclusive. Furthermore, due to the diversity of urban areas, it is necessary to understand PEDs holistically, distinguishing exactly what makes a district a PED or not, and then identifying archetypes and key elements that can help achieve the PED target from the earliest stages of design. Therefore, several important questions concerning PED definitions still need to be further discussed, including the elements computed in the energy balance, if corrective factors are needed to account for different contexts (e.g., high urban density versus low peri-urban or rural density), if a mathematical balance is sufficient, or if uncountable characteristics of the districts need to be considered [31].

PEDs design and sustainability. An effective and sustainable PED design requires a systemic and holistic methodological design approach that should consider technological complexity and environmental and socio-economic issues [32]. The current PED assessment methods are often sets of economic, energy and environmental indicators that are evaluated in isolation from each other without any substantial connection. However, in order to achieve PED targets in a conflating domains environment, all these aspects and many others, such as the social aspect, the life cycle approach and stakeholder engagement, need to be assessed together. Therefore, the need to address multiple and often conflicting objectives emphasizes the need for a holistic approach at all stages of the design process. In addition, all these aspects must be taken into consideration from the early design stages to identify the right way to achieve the target without the need to overhaul the development trajectory at subsequent stages.

Therefore, even though PEDs may have the ability to transform our cities, the journey leading to PEDs is indeed difficult and requires facing challenges on different levels at different stages of PEDs realization. There are both technical and non-technical challenges in creating an overarching vision and framework for PEDs. On the one hand, there is a need to define integrated holistic district-based tools, guidelines, and targets [33]. There will also be the need for new integrated district-level early design tools, which, although simplified, take into account the multidisciplinary and complexity of the investigated systems. On the other hand, it is necessary to respond to the needs of stakeholders and to develop sustainable business models.

Technologies within PEDs. The building sector offers significant potential for decarbonization and should be, together with the mobility and transportation sector, one of the core sectors undergoing substantial changes in order to reach decarbonization targets [34–37]. Due to the different issues in the implementation of PEDs, the specificity of the climate challenges, and the differences in energy needs, there is no on-size-fits-all technological strategy that can be applied everywhere to achieve the PED target. Instead, PED design should incorporate all available technologies, aiming to maximize renewable energy sources production over the year. It is also essential to identify synergies among different stakeholders (e.g., waste heat utilization from an industry) and leverage interactions with the wider grids (district heating, power grids, gas grids, etc.). In fact, the consideration of different energy networks and their interactions is critical for properly assessing the economic and environmental benefits of smart districts [38]. By doing so, it is possible to enhance the overall benefits of PEDs. However, this can be a challenging task, as the complexity increases drastically when considering the active management of interdependent vectors and relevant networks [39,40]. Moreover, the rapid evolution of technologies for energy efficiency and for integrating renewable energy into buildings will require a research-to-design approach [41,42].

Energy modeling of PEDs. This also illustrates the need for new approaches to modeling PEDs that are capable of taking into account their complexity while maintaining computational tractability. In recent years, there has been an increasing number of papers dealing with energy modeling, analysis and the performance optimization of districts [43–49]. However, there are several issues when modeling the innovative components often available in PEDs. This affects the prediction accuracy and hinders direct comparisons [50]. In addition, the complexity due to the district scale requires new approaches compared to those designed for the analysis of individual buildings. Accurate district models also require many and varied inputs, which leads to data availability and accuracy issues. For instance, the predictions are often not as accurate as for single-building models, because it is difficult to schedule human behavior and urban climate and to characterize the complexity of a single building on a larger scale [51]. Other sources of uncertainty concern input data, meteorological data, geometry data, building energy modeling, energy system modeling, integrating mobility demands, user interface and complexity, modeling process and accuracy, and data integration. There is no single or standardized way to approach the integration of these issues, which can lead, again, to the incomparability of the models. Lastly, data management plans need to be established to manage the larger amount of data usually generated at the district level, if compared to the scale of a single building. Further research should be devoted to the modeling of PEDs that considers different possible factors describing the urban environment, in order to have a flexible approach that can be applied to different contexts.

PEDs and environment. Assessing the environmental impact at districts scale is a crucial step towards sustainable cities, and different recent studies have investigated environmental sustainability at the district level. The approach of assessing the environmental sustainability of PEDs varies, for example, in terms of system boundaries and environmental KPIs adopted as metrics [52]. However, there is a specific need for a standardized, replicable and transparent approach when assessing environmental impacts at the district scale, with different scopes and indicators.

PEDs and social inclusiveness. The implementation of Positive Energy Districts also requires new frameworks to offer a socially inclusive and affordable perspective for the inhabitants [53]. In fact, sustainable development cannot be successful in the provision of people's well-being until it addresses social sustainability. However, social sustainability and the respective assessment methodology specifically for PEDs are not as established as other aspects. In terms of the sustainability of urban developments, some of the important aspects of sustainable districts reflected in existing studies include effective and accessible local services, safety from crime and accidents, the provision of sustainable transport modes, aesthetics and urban landscape quality, the affordable price of housing, opportunities for social participation, good environmental conditions, and employment and opportunities for business [54]. The issue of energy poverty is also often mentioned as a social challenge worthy of attention [55]. However, in the context of energy communities, a quantitative framework for evaluating social impacts and benefits could be more structured.

PEDs economics and governance. The development of a PED, as reported above, calls for new energy networks and relationships among the building blocks of the built environment: power plants, energy and mobility infrastructures, buildings, storage systems. Apart from the technical challenge of making this interaction and energy sharing possible, there are novel implications related to business models and governance systems not yet deeply investigated and considered in their complexity. The costs associated with new energy management systems, trade-offs among thermal and electric energy, peak shaving services or providing users with "thermal comfort" instead of thermal energy are still partly open questions. Similarly, how to structure the governance (including responsibilities and legal implications) of energy communities is an ongoing debate, and the willingness of different stakeholders to participate in such initiatives should not be taken for granted.

Stakeholder engagement. Widely recognized as one of the challenges in (and barriers to) the implementation of PED projects is stakeholder engagement in the planning and implementation phases of PEDs [56]. Firstly, this is due to the variety of involved parties in PEDs. Not only are municipal agencies concerned with the planning, development and governance of the city districts involved, but so are energy contractors, real estate companies, business owners and citizens in the area, who may have had a limited relationship with each other until now. Also, with an increase in complexity, the importance of stakeholder management arises [57]. Therefore, a better understanding of the stakeholder environment and its efficient management would increase the chances of success. In this context, the prevailing discussions on stakeholder engagement in the PED literature could further benefit from a systematic approach toward stakeholder mapping and clarifying how stakeholder engagement can be structured and organized. Within this framework of general research gaps, the dichotomy between technical/modeling/design issues in the field of PEDs and the connection to the social sphere and stakeholder interaction may appear difficult to reconcile, presenting peculiar challenges in the diffusion of the concept of PEDs for the decarbonization of the built environment.

Within this perspective, the concept of co-creation, or, in other words, the possibility of creating innovations outside of research centers and universities (arising from a bottom-up perspective in connection to all stakeholders of the sector), is of interest in several domains. Therefore, this paper aims to contribute to covering the aforementioned research gaps and describe potential ways forward with such a co-creation approach. The described work is based on the outcomes from a workshop organized by IEA EBC Annex 83. The workshop was centered around stakeholders' engagement in PEDs, seeking to investigate the abovementioned issues and co-create on the topic of the future evolution and next steps in PEDs. The main objective of this approach was to foster knowledge exchange, collaboration, and the development of effective strategies that will ultimately strengthen the successful implementation of Positive Energy Districts. This paper aims to report the main findings of this collaborative co-creation exercise, in order to provide a concise view of the current limits and potential ways forward for research in the field of Positive Energy District design and performance assessment.

2. Methodology

During the conference "Smart and Sustainable Planning for Cities and Regions", which took place between July 19th and 22nd 2022 in Bolzano (Italy), IEA EBC Annex 83 organized a workshop titled "Sharing the experiences on Positive Energy Districts: Lessons learned from Annex 83". There were more than 40 participants from various fields of study and domains (energy and systems engineering, urban planning, architecture, building engineering, economics), representing mainly academia but also both public and private sectors, with a particular focus on energy systems and solutions, PED and PEB implementation, and urban planning. The participants represented a demographic group of 25–50-years-old, both women and men. The aim was to establish an environment of stakeholder co-creation to validate the methodologies, results and ideas developed within Annex 83 while establishing some specific issues and future work. With this goal, the preparation of the workshop and the workshop itself was organized in the form of a World Café, a method which allows for effective and well-designed group discussions [58]. The World Café methodology is a straightforward and adaptable format for facilitating large group dialogues.

The World Café can be tailored to various needs, considering context, participant numbers, purpose, and location, which shape the event's design, invitation, and questions. The core model includes

- Setting: a café-like environment with small, round tables, tablecloths, colored pens, sticky notes and any interaction tool available.
- Welcome and Introduction: the host offers a welcome, introduces the World Café process, and sets the context.
- Small-Group Rounds: three or more twenty-minute rounds of conversations occur in small groups. Participants switch tables after each round, with one person optionally remaining as the "table host" to brief newcomers.
- Questions: each round starts with a context-specific question. Questions may remain constant or be built upon each other to guide the discussion.
- Harvest: participants share their discussion insights with the larger group, often visually represented through graphic recording.

The methodology has both the strengths and the weaknesses of co-creation approaches: it is dependent on the focus group participating and the formulation of the questions and timings chosen, but when structured correctly, it is effective in collectively generating knowledge and jointly framing replies to complex problems and questions.

The methodology steps followed are reported in Figure 1.

Figure 1. Methodology steps.

Every methodological step will now be clearly described:

1. **Objectives of the workshop and preparation.** The first step of the World Café approach is to identify the main objectives. For this workshop, there was the need to investigate the current landscape of PED research, as well as to have a benchmark and collect feedback on the current research activities within Annex 83. Questions were structured in order to frame the current state-of-the-art understanding of the topic.
   A mapping of the potential different stakeholders in the PED design and implementation process was carried out at this stage.
   As a result, municipalities, community representatives, energy contractors, real estate companies and commercial facilitators, as well as citizens, were identified as main target groups. Later, the follow-up discussions were built around these main actors. Further, the mapping of the stakeholders' involvement was carried out for better understanding the complexity of relationships, roles and synergies as well as the impact on the design, implementation and operation stages of PEDs.

2. **Collaborative action planning and execution of the workshop.** The second step included collaborative action planning and workshop execution. The activities were initiated with brief presentations from the Annex 83 Subtask leaders, in order to present the activities of the workgroup and allow the participants to frame and put all questions into context.
   To achieve a successful interactive discussion, the collection of the answers was done using the World Café format, a form of conversation and knowledge sharing where the participants are divided into smaller groups so that everyone has a chance to share their opinion or thoughts. In this workshop four tables were formed, one for each IEA EBC Annex 83 Subtask (ST-A Definitions and context, ST-B Methods, Tools and Technologies for Realising Positive Energy Districts, ST-C Organizing principles and impact assessment, ST-D Demos, implementation and dissemination). Each of the tables had three questions prepared covering main activities and focal aspects of the respective Subtask, resulting in twelve questions in total (Table 1). Thanks to the 20-min interval sessions, when groups were shifting between the tables, all participants had sufficient time to work on all the provided questions. During each session, the participants were asked to provide their answers and share their opinions to the given questions. They were also encouraged to discuss among their team members their views on the provided topics, as well as to identify the concrete actions and responsibilities, in addiction to impacts and timelines. At the end of the workshop, the answers were collected and structured, grouping together and categorizing the most similar and popular answers.

3. **Documentation preparation and follow-up activities**. The results of these discussions were elaborated to create a comprehensive document that could be promoted among a broader research community, to raise awareness of the importance of stakeholder engagement in PED development. Additionally, as a dissemination stage of the workshop, highlighting the key insights and recommendations, the results are presented in Section 3 of this paper. For the purpose of this work, the twelve questions listed in Table 1 were arranged in thematic topics for easier reading. These thematic areas of interest are synthetically reported below:

- Positive Energy Districts' definitions and fundamentals (Section 3.1).
- Quality-of-life indicators in Positive Energy Districts (Section 3.2).
- Technologies in Positive Energy Districts: development, use and barriers (Section 3.3).
- Positive Energy Districts modeling: what is further needed to model PEDs? (Section 3.4).
- Sustainability assessment of Positive Energy Districts (Section 3.5).
- Stakeholder engagement within the design process (Section 3.6).
- Tools and guidelines for PED implementation (Section 3.7).

Table 1. World Café questions.

	Question #1	Question #2	Question #3
ST-A *: Definitions and Context	What are the essential PED DNAs? Can generic PED archetypes be created based on them?	What are the categories of quality-of-life indicators relevant for PED development?	How would you use a database tool to learn about PED development process (e.g., using static information for dynamic decision-making)?
ST-B *: Methods, Tools and Technologies for Realizing Positive Energy Districts	Which future technologies would you expect to be adopted in PEDs and cities?	What can be the challenges and the barriers in the future (regarding e.g., control, smart solutions, modeling, technologies) to PED development and diffusion?	What is your expectation for urban and district energy modeling? How can models help to shape PEDs and cities?
ST-C *: Organizing Principles and Impact Assessment	What is the impact of stakeholders in the PED design/decision process, what are their interests and how are stakeholders likely to be involved in the overall process?	What costs do you expect to bear and what revenues do you expect to realize from the PED implementation? Which aspects should be included in the organizational/business models?	What would you prioritize in terms of energy aspects or efficiency and social implications of living in a PED? Which aspects are more relevant for you?
ST-D *: Demos, Implementation and Dissemination	Annex 83 together with other PED initiatives is developing a database of PEDs and PED-Labs: what would be your main interest in consulting the database?	Having the outcomes from PED guidelines analysis, what information would be the most interesting for you to see?	Who can benefit from the PED research studies and Annex 83 results? Which stakeholders are interested?

* https://annex83.iea-ebc.org/subtasks (accessed on 30 June 2024).

3. Results

3.1. Positive Energy Districts Definitions and Fundamentals

What are the essential PED DNAs? Can generic PED archetypes be created based on them?

With the implementation of more PED cases across Europe, it is feasible to collect and extract data from PEDs in cities and countries, with different boundary conditions. Through analyzing these data, it might be possible to identify common characteristics among existing PED cases and develop a set of generic PED archetypes. A crucial aspect of PED archetype development lies in the selection of key PED characteristics to be considered. The key characteristics identified during the World Café session were grouped into four main clusters: Facts and Figures, Technologies, Quality of Life, and Others (Table 2).

The first category of characteristics (i.e., Facts and Figures) refers to the main statistics of the PEDs, including population, geographic location, climate characteristics, population density, built form, land use (e.g., residential, commercial, and industrial buildings), and key energy-related statistics (energy demand and renewable energy potential).

Furthermore, the Technologies category includes key technological strategies adopted for achieving the PED targets (renewable energy supply mixes, energy efficiency measures, characteristics of the energy system networks, the presence of storage and mobility solutions).

Table 2. Key identified characteristics of PEDs.

Categories	Key Characteristics
Facts and Figures	Physical sizes/population size
	Geographical location
	Climate
	Density
	Built form
	Land use
	Energy demand
	Renewable energy potential
Technologies	Renewable energy supplies
	Energy-efficiency measures
	Energy distribution (e.g., co-generation, district network)
	Energy storage
	Mobility solutions
Quality of Life	User comfort
	Social-economic conditions
	Health impacts (e.g., air pollution, noise pollution)
	Accessibility to green space
	Accessibility to services (e.g., bike lane, public transportation)
	Local value/sense of community
Others	Regulations/Policies
	Stakeholder involvement
	Local targets and ambitions
	Local challenges
	Impacts of PEDs

The Quality-of-Life category instead collects characteristics related to the inhabitants' well-being and social inclusiveness (user comfort, socio-economic conditions, health impacts, accessibility to green space and to services, local value/sense of community).

Finally, the Other category includes stakeholder engagement and economic and governance characteristics, including regulations/policies, local challenges and the impact of PEDs.

These identified characteristics need to be prioritized, and the most important ones underlying the PED identity will be further explored. It is expected that different stakeholders might prioritize the PED characteristics differently, and a survey might be conducted with different stakeholders to understand their priority, in order to decide which characteristics are to be considered in PED archetype development.

3.2. Quality-of-Life Indicators in Positive Energy Districts

What are the categories of quality-of-life indicators relevant for PED development?

Considering indicators for the quality of life of occupants in PEDs, the most relevant items mentioned in the workshop are briefly summarized in Table 3. The grouping of the quality categories was conducted afterwards by the workshop facilitators. A split becomes evident between "tangibles" and "intangibles", with the latter being very difficult to assess, or a fortiori, to measure. It was pointed out that the quality concepts may depend much on the local context. Next to this, the need for properly balancing social and ecological requirements was an equally popular opinion.

Table 3. List of identified "tangible" and "intangible" quality categories.

Type	Quality Categories	
Tangible	Indoor and outdoor environmental quality	Physical quality and comfort of the environment
		Security and safety
	Level and accessibility of servicing	Public and active transport facilities including walkability, energy services (access to affordable energy including access to energy efficiency), sustainable waste management
		Access to daily life amenities including education, culture, sports, coworking and study places, provisions for children, but even common gardens or community kitchens
		Aesthetic quality
		Functional mix
		Future-proofness
		Acceptable cost of life (affordability, inclusivity)
		Equity and just transition
		Functional links to realizing circularity and reducing emissions
	Citizen engagement	Involvement in decision-making
		Social diversity in participation
	Access to greenery	The possibility to reconnect with nature
		Sufficient open space
	Information flow	From creating awareness over enhancing knowledge and literacy up to capacity of control
		Transparency on energy flows and information for the end prosumer
		Insight in applicable PED solutions and in healthy lifestyles
Intangible	Sense of well-being	
	Quality of social connections	
	Sense of personal achievement	
	Level of self-esteem	
	Sense of community	
	Degree of cooperation and engagement for the common interest	
	Time spent with friends (outdoor)	
	Budget available at the end of the month to spend freely	
	Not being aware or realizing of living in a PED	

The first main family of "tangible" quality categories to be discerned consists of indoor and outdoor environmental qualities. These are the physical quality and comfort of the environment, such as temperature, air quality, noise, and the local microclimate. It also includes aspects such as security and safety. The second would be the level of accessibility of servicing, which covers public and active transport facilities, including walkability, energy services (access to affordable energy including access to energy efficiency), and sustainable waste management. Also, the access to daily life amenities such as education, culture, sports, co-working and study places, provisions for children, and even common gardens or community kitchens are discussed. Other identified categories are aesthetic quality, functional mix, and future-proofness. This must come at an acceptable cost of life (affordability, inclusivity). Equity and just transition must be assured. Functional links to realizing circularity and reducing emissions are also pointed out. Next comes citizen engagement—involvement in decision-making, as well as social diversity in participation. Access to greenery and the possibility to reconnect with nature, as well as the presence of sufficient open spaces, constitutes another group. Lastly, there is the category dealing with information flow, addressing the whole range from creating awareness and enhancing knowledge and literacy to the capacity of control. It also includes transparency around energy flows and information for the end prosumer, insight into applicable PED solutions, and healthy lifestyles.

Apart from the above groups, "intangible" series of quality aspects are also mentioned. They are substantially different in character and cover aspects such as sense of well-being, quality of social connections, sense of personal achievement, level of self-esteem, sense of community, degree of cooperation, engagement in common interests, time spent with friends (outdoor), and having a budget available at the end of the month to spend freely. Some participants point to the ultimate quality confirmation: not having to know or realize that one lives in a PED.

Especially with the "intangible" aspects of quality of life, we can question if it makes much sense to dedicate major efforts to measuring and assessing these, or, on the other hand, one could better concentrate on setting up an effective governance process for the PED that assures that those aspects are being adequately addressed while consulting the entire stakeholder community. This would need to include the stakeholders that often remain silent; for example, those who can be associated with vulnerable groups. An effective and "just" governance process could thus help to ensure that intangible quality factors are being properly addressed and ultimately guaranteed.

3.3. Technologies in Positive Energy Districts: Development, Use and Barriers

Which future technologies would you expect to be adopted in PEDs and cities?

From the provided answers of the audience, five main groups of technologies were defined:

(1) Energy efficiency.

(2) Energy flexibility.

(3) E-mobility.

(4) Soft mobility.

(5) Low-carbon energy generation.

These groups are related to the pillars identified in [59] and are seen as potential technologies for the future and energy transition (through PED implementation or other deployments). The list of technology solutions for the technology groups is listed in Table 4 and further discussed below.

In terms of energy efficiency, the participants highlighted the importance of reducing energy demand in PEDs and cities through the integration of new efficient buildings and building retrofitting. Also, the need to minimize the consumption of other resources, such as water, and to reduce waste and CO_2 emissions were discussed. To achieve this goal, technologies such as carbon capture and storage (CCS) and nature-based solutions (natural sinks), efficient resource management, and efficient water systems for agriculture (smart agriculture, hydroponics, agrivoltaics, etc.) could be used. One of the examples was the case of Evora [60], where the PED concept includes the renovation of heritage buildings using organic photovoltaics and a circular approach (second-life electricity storage devices).

In terms of energy flexibility, several technologies (software and hardware) were emphasized during the workshop. Regarding hardware, technologies such as storage (long term and short term), monitoring systems (sensors, smart meters, PLCs, energy management systems, etc.), vehicle-to-grid, heat pumps, and electronic devices like IoT technologies will need to be integrated. This contributes to the perspective highlighted by Zhang, et al. [61], with the growing importance of improving the interoperability and standardization of the systems to be able to boost digitalization in cities. At the building and district levels, stakeholders imagined the buildings to be fully automated with real-time behind-the-meter monitoring and automated actions. Stakeholders also underlined the importance of cybersecurity, data rights, and data access. However, if this ideal scenario is not possible, demand management and the remote control of devices should be used. This flexibility needs to be combined with low-carbon generation to ensure the resiliency of the district, i.e., that the impact on grids is minimized.

Table 4. List of identified possible future technology solutions in PEDs.

Technology Groups	**Solutions**	
Energy efficiency	New energy-efficient buildings and building retrofitting.	
	Nature-based solutions (natural sinks) and carbon capture solutions (CCS)	
	Efficient resource management	
	Efficient water systems for agriculture (smart agriculture, hydroponics, agrivoltaics, etc.)	
	Organic photovoltaics and a circular approach (second life materials, like batteries)	
Energy flexibility	Hardware	Storage (long-term and short-term)
		Monitoring systems (sensors, smart meters, PLCs *, energy management systems, etc.)
		Vehicle to grid
		Heat pumps
		Electronic devices like IoT * technologies
		Buildings fully automated with real time monitoring behind-the-meter and automated actions
		Cybersecurity, data rights and data access
		Demand management and remote control of devices
	Software	Edge computing
		Machine learning
		Blockchain
		Digital twins
		5G
		City management platform and platforms for city planning (space, refurbishment, climate change, etc.)
E-mobility	Promotion of shared vehicles over individual car use, lift sharing, and alternative ways (like micromobility) to collective transports	
Soft mobility	Promotion of a lifestyle that require less use of cars, i.e., “soft mobility” solutions like low emission zones or banning the entrance of some type of car (e.g., Singapore and Iran have policies in place to allow only certain car groups to drive freely in certain periods)	
	E-vehicle charging stations and vehicle-to-grid solutions	
Low-carbon generation	Photovoltaics	
	Energy communities	
	Electrification of heating and cooling (H&C) using heat pumps, district heating networks utilizing waste heat, or solar thermal technologies	
	Virtual production	
	Fusion technology	

* PLC = Programmable Logic Controllers, IoT = Internet of Things.

Regarding software, solutions such as edge computing, machine learning, and blockchain are seen as the key enablers of energy flexibility. In order to manage it at city level, solutions such as digital twins, 5G, city management platforms, and platforms for city planning (space, refurbishment, climate change, etc.) will need to be used. At the same time, at the citizen level, smart digital interaction through apps and services is required to engage with individuals, allow them to participate in activities, and encourage them to use their energy more wisely. Additionally, the use of citizen cards was also mentioned as a way to monitor personal performance [62].

As enablers, business models will need to be defined to promote the participation of PEDs and cities in energy markets (for example, through aggregation, peer-to-peer energy trading, sell flexibility to the market, etc.) [63], as well as to improve the capacity building of the city staff, citizens (to ensure inclusion), and workforce involved in these implementations [64].

Regarding mobility (private and public), two main issues were under discussion. The first issue was the promotion of e-mobility through shared vehicles over individual car use, lift sharing, and alternative means (like micromobility) of collective transport. The second was the promotion of a lifestyle that requires less use of cars, i.e., "soft mobility" solutions like low-emission zones or banning the entrance of some types of cars (e.g., policies to allow only certain car groups to drive freely in certain periods). E-vehicle charging stations and vehicle-to-grid solutions were also emphasized to promote both green mobility and energy flexibility.

Lastly, low-carbon energy generation was seen as a key driver for decarbonizing cities and implementing PEDs. Photovoltaics is the most commonly used technology in PEDs. Energy communities can serve as a catalyst for its widespread installation while also encouraging collective participation. The electrification of heating and cooling (H&C) using heat pumps, district heating networks utilizing waste heat, or solar thermal technologies were mentioned as contributors to the decarbonization of H&C. As PEDs and cities face a problem of space availability for technology implementation, especially in areas of high urban density [59], renewable energy production assets outside the geographical boundaries of a PED could be contractually assigned to the PED, establishing a "virtual" boundary for the PED that is different from its geographical limits.

In conclusion, while it is worth remembering that the technological side is not the only one to be pursued when addressing PED performances and implementation, it is also important to highlight that all the five areas of technological advancement mentioned (and as presented in the paper) contribute significantly to addressing specific PED challenges:

(1) Energy efficiency—being able to meet a positive energy balance while limiting the overall energy demand—is crucial in guaranteeing resource efficiency and optimizing circularity.
(2) Energy flexibility options are crucial in guaranteeing a feasible and optimized interaction between energy generation and consumption, moving towards the improved management of cities.
(3) E-mobility is fundamental in the electrification process and in the optimization of the transport sector's consumption.
(4) Soft mobility aims to target the social change required to reduce consumption in the transport sector.
(5) Low-carbon energy generation in the general framework of all other solutions mentioned is aimed at reducing and optimizing energy consumption, and it is crucial in generating the required remaining energy through low-carbon means.

What could the challenges and the barriers be to PED development and diffusion in the future (regarding, e.g., control, smart solutions, modeling, technologies)?

The implementation of PEDs and its related technologies in cities could encounter several challenges and barriers. Table 5 categorizes the challenges discussed in the stakeholder workshop into different key areas. These challenges include capacity building and policy, social aspects, finance, data management, and other factors, providing a comprehensive overview of the challenges that need to be addressed for successful technology implementation.

Similar outcomes can be traced in several examples from the literature [65], and these indications are coherent with other views in state-of-the-art research. The main barriers and problems for PED implementations are briefly described in the following paragraphs.

Table 5. Key topics of challenges and barriers in PEDs and technologies for decarbonizing cities.

Challenges and Barriers	Key Topics
Capacity building and policy issues	Political and legal barriers
	Regulatory frameworks and policy constraints
	Tailored legislation
	Bridging the knowledge gap
	Inadequate data sharing practices
	Securing sufficient financial resources
	Lack of clear regulations defining PED classification
	Active involvement of policymakers
	Widespread dissemination of knowledge
	Collaborative data-sharing efforts
	Securing adequate funding
	Establishing supportive policies and regulations
Social challenges and considerations	Cultural barriers
	Access to affordable and sustainable energy for all
	Building social agreements and fostering collaboration
	Energy literacy
	Addressing personal behavior acceptance
	Transition strategy for inclusivity
	Social inclusion and trust-building
	Data sharing and privacy concerns
	Overcoming public opposition and promoting knowledge dissemination
Financial barriers	Long-term storage investment and space competition
	Insufficient investment
	High upfront costs
	Allocation of costs among stakeholders
	Incentives for participation
	Addressing investment challenges for different stakeholders
	Accounting for battery costs
Data management	Data standardization
	Data security measures and protocols
	Sustainability and maintenance of data infrastructure
	Privacy regulations and data anonymization techniques

Table 5. *Cont.*

Challenges and Barriers	Key Topics
Sustainable business models and ownership structures	Standardization of control technologies and replication strategies
	Grid management approaches
	Deep penetration of sustainable technologies
	Implementation of predictive models Long-term maintenance activities and resident data collection
	Balancing diverse requirements
	Addressing grid operation challenges
	Managing multiple independent energy districts
	Inclusivity strategies for digital technology reliance
	Managing production peaks and defining the role of buildings and districts
	Effective management strategies for grid congestion and stability

Capacity building and policy issues present significant obstacles for PEDs, as bridging the knowledge gap among the general public, administrators, and city-level operators is essential for successful PED implementation. A long permission process or limitations surrounding technology size are legal and bureaucratic barriers that hinder their progress, necessitating to address that we address regulatory frameworks and policy constraints. Tailored legislation is crucial to clarify permissible activities within private grids in PEDs, ensuring fairness and equality, such as peer-to-peer trading. It is also worth mentioning that securing sufficient financial resources is a significant challenge, given the difficulties in obtaining capital for PED implementation. Moreover, clear regulations defining PED classification criteria are lacking, and this reinforces the need for a structured definition, as well as standardized guidelines and frameworks [31]. To overcome these obstacles, the active involvement of policymakers, widespread dissemination of knowledge, collaborative data-sharing efforts, securing adequate funding, and establishing supportive policies and regulations should be critical steps forward.

Social challenges and considerations must also be addressed in PED implementation. Cultural barriers, including heritage preservation, can impede the integration of new energy solutions into established urban environments. Ensuring access to affordable and sustainable energy for all community members is crucial in addressing energy poverty. Building social agreements and fostering collaboration among stakeholders are key to establishing consensus and collective action for PEDs. Energy literacy empowers individuals to make informed decisions and actively participate in energy-related matters. Achieving broad societal acceptance requires addressing personal behavior acceptance, enabling individuals to adjust their energy usage within a comfort range while maintaining efficiency. A transition strategy is necessary to avoid excluding certain populations, such as the elderly or those less familiar with advanced technologies. Social inclusion and trust-building among stakeholders facilitate knowledge exchange and collaboration among producers, operators, and users. Data sharing poses challenges due to privacy concerns, necessitating robust data protection measures. Overcoming public opposition and promoting knowledge dissemination are crucial for garnering support and engagement in PED initiatives.

Also, financial barriers stand as significant challenges in successful PED implementation. The need for long-term storage creates investment and space allocation challenges, requiring proper infrastructure support. Moreover, specific investment challenges faced by different stakeholders, including prosumers, need to be addressed. Without sufficient investment, the realization of PED projects may remain beyond reach, while the upfront costs pose financial constraints. Meanwhile, the high upfront costs associated with implementation can impose financial constraints. Fair cost allocation among stakeholders and incentives in the form of financial benefits or subsidies can enable us to overcoming the financial barriers in this regard.

Effective data management is critical for successful PED implementation. Data standardization ensures compatibility and interoperability among systems and stakeholders within the PED, facilitating seamless integration and analysis to optimize performance. Robust data security measures and protocols are necessary to protect the sensitive information collected and stored in PEDs. Sustainability and the maintenance of data infrastructure ensure continuous and reliable data availability for monitoring and decision-making. Privacy regulations play a significant role in governing data-sharing practices, requiring a careful balance between accessibility for research and development, and safeguarding individual privacy rights. Adhering to privacy regulations and implementing data anonymization techniques can address these concerns.

Developing sustainable business models and ownership structures that ensure the long-term viability of Positive Energy Districts (PEDs) is a critical challenge. Standardizing control technologies and replication strategies is essential for facilitating the widespread adoption of successful PED models. The absence of energy storage solutions puts substantial pressure on the grid, necessitating innovative approaches to grid management. Achieving a deep penetration of sustainable technologies and implementing predictive models for proactive actions are vital for optimizing PED performance. Additionally, conducting long-term maintenance activities and gathering resident data on carbon footprints are important for effectively tracking and adjusting PED activities. Balancing diverse requirements, such as water, energy, and biodiversity needs, presents challenges in determining priority areas.

Moreover, addressing grid operation challenges, including high grid loads and congestion, is necessary for PED integration. Furthermore, developing and implementing PEDs requires significant time and resources, and managing multiple independent energy districts can involve substantial overheads. The heavy reliance on digital technologies may pose barriers for individuals or communities less familiar with advanced technologies, necessitating inclusive strategies. Managing production peaks within PEDs and defining the role of buildings and districts in future energy systems pose additional challenges. Effective management strategies are required to address grid congestion resulting from high demand and complex energy flows, ensuring grid stability.

3.4. Positive Energy Districts Modeling: What Is Further Needed to Model PEDs?

What is your expectation for urban and district energy modeling? How can models help to shape PEDs and cities?

Modeling plays a crucial role in the context of Positive Energy Districts (PEDs), as it offers valuable outputs that can be utilized by various stakeholders. Simulating district energy systems using modeling or optimization tools can improve the system's efficiency and economic benefits. During discussions on barriers in PED modeling, several requirements for future modeling were identified, which can be broadly categorized into the model's aim and its target audience. The main findings are summarized and categorized in Figure 2, showing barriers and enablers with respect to the stage in which the energy model is used.

The modeling objective includes a range of purposes, from simulating energy system components to real-time monitoring and control. The specific aim of the model depends on its intended use, whether it is for public education, city-level decision-making, or research purposes to improve the technologies.

Effective modeling leads to improved design and control at both the building and district levels. To simulate the behavior of multiple components under different operating conditions, efficient and accurate physical models are required. These physical models can be automated using design architecture templates or providing users with total control. Additionally, data-driven approaches, such as digital twins, are gaining significance for real-time system monitoring, control, and maintenance.

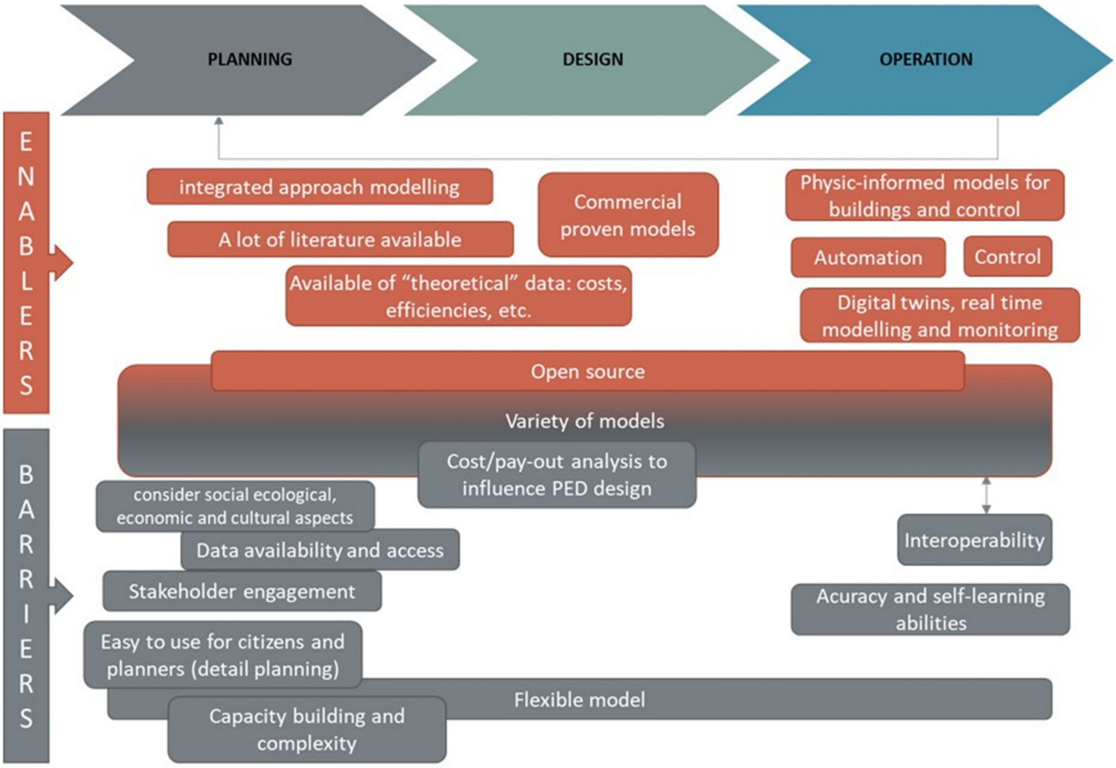

Figure 2. Overview and categorization of PED modeling insights.

However, the availability of open-source modeling tools with clear instructions on how to use them is still lacking. While several tools for modeling PEDs have been developed, there is a need for an inclusive, accessible, and user-friendly resource that introduces each model and its application, which was highlighted by the stakeholders. Such a resource would facilitate model implementation and connection with relevant tools. Several review papers have conducted a multi-criteria analysis (MCA) on existing modeling frameworks and tools, with some specifically focusing on properties and structural features of ESMFs [66,67]. Lyden et al. [68] reviewed 13 tools capable of modeling renewable energy systems, demand-side management, and storage, proposing a selection process for different applications. Tozzi and Jo [69] also compared 14 tools for simulating or optimizing renewable energy systems. Hall and Buckley [70] analyzed the UK's 22 most common energy system models, while Ringkjøb et al. [71] reviewed 75 modeling frameworks and tools used in electricity systems. However, despite the development of numerous energy system modeling frameworks, there are still several gaps to be addressed. The main one is the absence of a fully automated framework for modeling energy systems. Currently, most of the process is conducted manually, which is complex and time-consuming. An automated framework would greatly benefit non-expert users like urban planners and real estate developers. Additionally, there are data-related gaps, such as a lack of data with appropriate temporal resolution and transparency and accessibility issues, leading to uncertain assumptions. Moreover, many frameworks only focus on technical aspects and neglect socio-political and indirect costs associated with energy systems, particularly those involving new technologies. In the energy transition context, modeling is essential as it provides valuable information for municipal planners and researchers. City-level decision-making models should incorporate social, ecological, and cultural information to make informed choices. The model needs to be flexible to accommodate the evolving project stages, also capturing additional details effectively. An inclusive system modeling approach that considers various elements of PEDs, including climate change adaptation and energy communities, can raise public awareness and accelerate the energy transition process.

3.5. Sustainability Assessment of Positive Energy Districts

What costs do you expect to bear and what revenues do you expect to realize from the PED implementation? Which aspects should be included in the organizational/business models?

The sustainability assessment always includes economic and financial aspects into the analysis. A large contribution in this sense derives from the literature and market experts, as mirrored during the World Café discussion, although two main themes are still open to discussion. The first one regards the dimension of the district, and the second one is the site-specific nature of business models. Organizational and business models are largely available for buildings, with the diffusion of a shared approach for energy production and consumption that yields an increase in the total investment costs in the case of a single building. This estimation is not easily derived for districts, as it is not possible to associate a linear increase in costs with the increase in the number of buildings (and, in any case, assuming that any other transversal aspects are neglected). Moreover, business models are usually site-specific and incorporate financial and economic aspects that are not replicable for other urban areas. It seems that there is a parallelism between the wide diffusion and interest in the rating systems of buildings (recognized as a valuable feature by the market) and the little use of rating systems for neighborhood districts (despite the large number of available models and tools). Therefore, a way to gain advantages from the scalability of these models could be recognized in the definition of PED typologies or archetypes that can be replicated in some specific cases, or under specific underlying conditions.

Positive energy also implies shared systems. As emerged from the discussion, if, on one side, the chance to share technologies and energy is considered beneficial to reduce the bill costs, on the other side, it introduces an investment risk. In this sense, shared systems can be perceived as a problem multiplier more than a problem-solving measure. There is a different perception of the two scenarios—of owning a PV system on the rooftop of the building with a precise consciousness of the investment costs and bill reduction, or using energy from the neighboring buildings and paying for the decentralized supply instead of the centralized one. To avoid disparities in energy market participation and speculation from energy production systems owners, feedback from the stakeholders suggested that the appointment of a non-profit entity for the management of the PED could be a good option to ensure transparency and control. Quantifying the potential interest of the public in participating to the governance bodies and activities of such an entity is a challenging task.

Another critical point of discussion for PED business models concerned the inclusion of social aspects. Indeed, environmental aspects are included in an easier way in the analysis, especially if they entail the definition of fees or incentives dedicated to mitigating climate change. However, if the environmental debate is more easily encompassed in the economic models, the same does not apply for social aspects. Models are mathematical descriptions of a system and use formulae, languages and concepts that can be "measured". Thus, to include social aspects in business models, a translation of some quality aspects into monetary values should be imaged and conceptualized. This approach should be carefully applied by deeply involving local stakeholders and those directly and indirectly impacted by any aspect of the PED development (therefore, identifying and mapping them in advance), as social values and impact may widely vary. Without any doubt, some social and environmental aspects are easier to be quantified than others, such as the increase in employment or the surface of green areas in PEDs. The health benefits, interactions among the inhabitants due to more favorable public living spaces or cultural heritage valorization, and architectural/aesthetic quality are examples of benefits more difficult to be quantified.

The results of the discussion are proposed in Table 6, following the "10 types of innovation" structure suggested by Doblin (an innovation-focused firm, now owned by Deloitte), which is usually adopted to identify what type of innovation is enabling a company to emerge from competitors. This assumes that a PED should be, in a certain sense, a mix of advanced energy products and services, but in the end, also an investment that makes sense for the promoters, the users and the local authority.

Table 6. Expected costs to bear and revenues from PED implementation.

Categories of Innovation	Innovation Types	Possible Revenues/Advantages in PED Business Model/Governance	Possible Costs/Drawbacks in PED Business Model/Governance
Configuration	Profit Model	Providing thermal comfort instead of a certain amount of thermal energy to inhabitants	Misconducts or rebound effect
	Network	Inclusion of the PED into larger projects and international networks, possibility of co-financing and knowledge sharing	Misalignment or delay of the PED project to the original timeline due to constrains related to international activities and networking
	Structure	Participation of the real estate companies/investors in the development and management of the energy infrastructure and EV mobility services as well as building management Free or almost free thermal energy supply from "waste energy" sources	Lack of knowledge, involvement in activities out of the usual business of investors Failure of the network due to unliteral decisions of a member in ceasing the provision of energy
	Process	Involvement of future inhabitants in the design phase of the energy community since the early stage, to share the sense of belonging and ownership	Reluctancy of inhabitants to participate in additional expenses or being involved in "entrepreneurial" activities or bored by the participation in boards and governance structures
Offering	Product Performance	Investors and companies involved in the PED development take profit from their role of frontrunner placing them before the competitors or entering in new market niches	Hi-tech BA and BEM systems may result costly in O&M, because of digital components, cloud and computing services, rapid aging of technology
	Product System	Including EV available for PED users may generate new incomes and reduce the need of individual cars. The integration of EV in the energy system may offer "flexibility services"	Lack of knowledge, involvement in activities out of the usual business of investors/real estate companies. Low interest of users in participating to the flexibility market, because of discomfort (unexpected empty battery of the EV)
Experience	Services	Provision of high tech and high-performance buildings, with outstanding energy performances (lower heating/cooling costs) and sophisticated Building Automation and Energy Management systems	Sophisticated Building Automation and Energy Management systems may result "invasive" to users, asking for continuous interaction with complicate systems, or leaving them not enough freedom to choose (e.g., opening the windows is not possible to achieve some energy performance)
	Channel	The PED is promoted as a rewarding sustainable investment, this allows the city to attract more clean investments (public funds, investment funds, donors), speeding up the energy transition	The communication of the characteristics of the PED is not done in the proper way
	Brand	Gold class rated buildings may have an increased value on the market, resulting in higher selling and rental costs, occupancy rate. The high architectural quality is appreciated by the market	The Branding/certification of the PED is not recognized by the market as an added value. The development of the PED takes longer as expected. Technology failures during the implementation or operation phase create a bad reputation and discourage future similar activities
	Customer Engagement	The PED is available as a digital twin, users are engaged via a dedicated app, allowing interaction, communication, reporting, monitoring of bills, etc.	The PED is perceived by users (e.g., social housing tenants) as a hassle and not responding to their needs, because they have not been involved in the identification of peculiar traits since the beginning

What would you prioritize in terms of energy aspects or efficiency and social implications of living in a PED? Which aspects are more relevant for you?

As it is difficult to decide between these two different spheres, it could be useful to focus on the "implications" that one aspect may have for the other, instead of prioritization. Indeed, there is agreement that a sustainability strategy focusing on energy aspects may also help in targeting social values, including health implications, both mental and physical

(And vice versa, pointing to social parity and inclusion should also bring to the energy efficiency and the conscious exploitation of energy sources). In the specific case of PEDs, where renewable sources are considered crucial to target the zero-emissions balance, it is possible to link emission reduction to health advantages. At the same time, PEDs may foster social inclusiveness and enhance social interactions among neighbors, thus promoting a re-thinking of urban areas and pointing to a more human-centric vision of the districts, also enhancing social capital. In this direction, every action will impact the community, thus increasing the sense of participation and inclusiveness of inhabitants, as well as social responsibility for sustainable development and growth.

Therefore, PEDs may be beneficial to overcome the dualism between energy and social issues—for example, by ensuring fair access to energy for all citizens—and positively impacting the reduction of energy poverty in the areas, or preventing it from occurring. Even the dimension of the PED may have a significant role in achieving the energy efficiency and social inclusiveness targets in urban areas. Indeed, the larger the city, the more difficult the spontaneous social interactions among people become. On the contrary, smaller districts are more accessible from both the social and the energetic viewpoints. Citizens are more likely to feel involved in the PED and that their decisions effectively impact, or can be applied faster for the benefit of, the area in which they live or work.

Finally, there was consensus among the workshop stakeholders that, if targeting sustainability, moderation should be the key. PEDs can offer a widespread set of different technology options, but occupants, workers and, generally, all the stakeholders involved in the PED design should be prone to change with the implied modification of habits and routines. As an example, the dependency on cars should be reduced in small neighborhoods and, where practicable, walks or bikes should be preferred for reaching workplaces or the city center. Behavioral changes may be supported by using various nudging techniques; however social norms, gender issues, cultural bias and resistance to change are key factors, often overlooked, that should be taken into account and carefully considered. Lastly, the key takeaway workshop idea for this question is the following: while it is true that it is necessary to pursuing optimal technical ways to achieve the decarbonization of the built environment, it is not possible to achieve it, unless a pleasant place to live is offered.

3.6. Stakeholder Engagement within the Design Process

Who can benefit from the PED research studies and Annex 83 results? Which stakeholders are interested?

During the discussions, the participants identified plenty of potential beneficiaries of PED studies, which were then structured and grouped, as shown in Table 7.

Table 7. List of identified potential beneficiaries of PED studies.

Category	Beneficiaries
Citizens and communities	Citizens, inhabitants, residents, general public, local communities and neighborhoods, municipalities and provinces, energy communities, and socially disadvantaged groups.
City decision-makers and planners	City decision-makers, city planners, local authorities, policy-makers, public administrations, politicians, local and national governments.
Research	Scientists, publishers, and research organizations.
Private companies and technology developers	Private companies of RES technologies, ICT companies, start-ups and new companies, entrepreneurs, technology developers and other companies involved in local development (tech development and evaluation).
Energy providers	Energy providers, grid operators.
Education stakeholders	Students and teachers.
Non-governmental organizations (NGOs)	NGOs and other civil society groups

It was agreed that PED research can be a great support to push citizen-driven initiatives towards the clean energy transition, to increase energy efficiency and bring new jobs to the local market. Citizens, local communities, and especially socially disadvantaged groups can gain from these studies by implementing the identified solutions in the culture of the citizens. Also, decision-makers, local authorities, policy-makers, public administrators, politicians and government representatives, as well as city/urban planners, could base their actions on PED studies. They should use results from PED studies for better and more informed decision-making and adaptations.

Next, to support the shaping neighborhoods through planning and policy, PED studies should widely be used in research. Scientists and research organizations could use gathered data on PEDs to further advance knowledge on this topic and further support developing the methods. These findings are also meant to be used as information for carrying out meta studies or assessment studies, and to gain more experience in relation to PEDs.

PED studies are expected to be very effective, not only in higher academics but also at lower levels of education, starting with the early years of the schooling system. It is important that the complex findings are translated into simpler and easier-to-grasp language, so teenagers, children and less-educated groups are aware of PED solutions and the potentialities of a decarbonized future.

Another popular identified group of stakeholders is private companies and technology developers who are investors and implementers of the solutions. Companies focusing on renewable energy sources and investing in local development in regard to climate change and supporting smart environmental and urban technology solutions should be heavy users of the PED studies. Also, start-ups, technology developers, entrepreneurs, and single figures can use the PED studies for updates on new advanced technology solutions that should be then further developed and implemented in the local communities. However, not only tech developers, but also energy providers and grid operators, should be using these findings, as they can improve their solutions by analyzing the outcomes of newly established research.

Moreover, NGOs and other civil society groups were noted as PED study beneficiaries, as additional knowledge and data sources. Last but not least, the environment we live in—the urban eco-system—was identified as one of the beneficiaries. Whilst it is not a typical stakeholder to be identified, it is important to recognize that our environment is strongly affected by our actions, and that, in the longer run, using the outcomes of PED studies will have a positive impact on our environment. Even though PED development is currently mostly focused on well-developed urban areas, these studies will also support further initiatives in developing countries.

What is the impact of stakeholders in the PED design/decision process, what are their interests, and how are stakeholders likely to be involved in the overall process?

Stakeholders are usually identified as individuals with a vested interest in the sustainable development of the districts and whose actions directly affect or are affected by the formulation and implementation of sustainability strategies. When dealing with sustainability issues in urban areas, the more easily recognizable stakeholders are inhabitants and local municipalities. However, this dichotomic perspective must be enlarged to also include the numerous "hidden" stakeholders, whose involvement is fundamental for the decision-making stages of the PED design. The workshop led to the identification of relevant stakeholders, building owners, municipalities and mayors, local investors and real-estate developers, employers and employees, and also customers.

The interests of these different stakeholders are miscellaneous and vary across different activities that take place in urban areas, ranging from the economic competitiveness of energy tariffs to the need for greener public areas, safe places and social parity, as well as public services and mobility issues. As interests vary, so does their impact on the decision process and design of PEDs; therefore, one of the fundamental practices of sustainability assessment should focus on the stakeholders' recognition and direct involvement. To properly engage stakeholders in the PED design and foster the dialogue through different perspectives and experiences, specific and targeted information and dissemination campaigns must be conducted. It emerged that stakeholders are more likely to be involved if they gain a clear perception of their eventual benefits, i.e., translating the concept of "positive energy" into the environmental, economic and social advantages that could derive from their participation in the project. This gained awareness has then to be shaped into different and more punctual "messages", the content of which mostly depends on the stakeholder. Indeed, considering real estate developers and investors, it could be demonstrated how PEDs can be beneficial for them in terms of added value to the market in which they operate, proven, for example, by the chance to have a specific certification of "positive districts". The PED lens must also be applied for the industrial stakeholders and utilities, as their investment can be attracted by highlighting their need to stay on the market and eventually enlarge their market share.

The importance of collaboration should not neglect younger generations, which usually show more receptivity to their future and to sustainability and climate change issues. Similarly, the communications should be calibrated for them and their preferences through compelling and engaging "storytelling" (as emerged from the discussion). In this sense, it could be useful to provide examples of existing PEDs and the improved well-being of citizens in PEDs, focusing on the capability of PEDs to be a stimulus for long-term sustainability. Moreover, the communication among young people and teenagers is far-reaching and cross-sectional, with their messages often being conveyed using social networks. In this sense, sustainability strategies can benefit from their enrolment, with a wider dissemination of the benefits of living in a PED.

3.7. Tools and Guidelines for PED Implementation

Having the outcomes from PED guidelines analysis, what information would be the most interesting for you to see?

The deployment of PEDs requires guidelines and tools to implement and to show the PED value, from design and construction to operation, verification, maintenance, renovation and end of life. As part of the work carried out by Annex 83, Subtask D in its first phase has collected 25 PED guidelines from several countries, which were analyzed with text mining techniques [72]. The aim of these analyses is to identify the existing gaps to effectively support future PED implementation from all the potential perspectives. As further analysis will be carried out in the second phase, the workshop was addressed to collect all the desired information to be seen from such an analysis. During the workshop, participants were required to identify their interests for the development of consolidated PED guidelines. The outcomes were grouped into main categories, as shown in Table 8.

There was high interest to explore the PED implementation strategies. However, it was also pointed out that no standard approach, success factors, technologies or stakeholders were of interest. Additionally, some answers provided valuable references of on-going works in this direction, with a special mention of the work of Li and Lange [73]. Another point of concern is the uncertainty related with the PED definition, which should be better clarified and addressed. Other categories that were identified are boundaries (also related to the definition of the PED and need to set up the boundaries of the district to establish the energy balance, the number of buildings included, and also mobility), finance (financial mechanisms as well as support schemes), citizen engagement (one answer pointed out the need to develop citizen engagement further to empowerment), management (process management, organizing involvement, and information provision), policy (incentives and regional regulations), flexibility/grid interaction (choice of timesteps and a credit system for energy flexibility), and form (this category includes the dissemination of results in many forms, not restricted to traditional video).

Annex 83, together with other PED initiatives, is developing a database of PEDs and PED-Labs. What would be your main interest be when consulting the database?

Table 8. Identified topics needed in PED guidelines.

Category	Comments
Strategies	Most comments dealt with the strategies on how to achieve PEDs, that should focus on success factors of PED initiatives, technologies and stakeholders rather than a standardized approach
References	Useful information, special attention to Liwen Li, planning principles for integrating community empowerment into zero-carbon transformation
Definitions	Help to reduce uncertainty
Boundaries	Energy balance calculations, mobility, definition (of buildings)
Finance	Financial mechanisms, support schemes
Citizen engagement	From engagement to empowerment
Management	Process management, organizing involvement, information provision
Policy	Incentives, regional policies
Flexibility/Grid interaction	Timesteps, credit system
Form	Dissemination through video and other forms (not only written information)

The proposed database for stakeholder consultation is the PED Database (PED DB), which is being developed under IEA EBC Annex 83, CA19126 PED EU Networking and JPI Urban Europe. The PED DB entails over 150 parameters and 400 sub-parameters in order to define PEDs, its concept boundaries, technological and non-technological innovations and strategies, as well as policies followed [74]. The data provided for PED case studies, PED-relevant case studies, and PED Labs are presented in a geo-referenced mapping interface (www.pedeu.net/map, accessed on 24 June 2024), which is open-access [75]. The database is targeting municipalities and decision-makers to assist them in learning about PED development processes, as well as planning and implementing PEDs in their own context.

The stakeholders consulted during the World Café session were asked about their main interest in consulting the proposed PED DB.

The answers were grouped into nine different categories, with the following results (Table 9).

Most of the answers positively valued the possibility of finding lessons learned in real-life implementations. The interest in the results was also very important for the participants, while four of them specifically mentioned an interest in using the results from different PEDs as a benchmark to compare PEDs. To this end, not only the data analysis, but also the metadata, could help to make this comparison. This task involves the need to normalize results depending on several factors (size, location. . .), taking into consideration the limitations given to the data protection and privacy issues. Another subject of interest is to find a set of technologies and solutions and related economic parameters—outlining the investment costs and the cost–benefits—that could help to benchmark the different PED technologies in economic terms. Moreover, we established a reference to examine the possibility of learning how PEDs have dealt with citizen engagement, energy poverty in urban areas and the role of new prosumers. As in the case of the guidelines, the stakeholders mentioned the definition and boundaries, needing to standardize PEDs, and having a reference framework to establish the energy balance. Furthermore, stakeholders highlighted the role of contact persons able to give further details about the initiatives.

Finally, the regulatory framework delves into the rules, procedures, and requirements that drive and enable the spread of PED initiatives.

How would you use a database tool to learn about PED development process (e.g., using static information for dynamic decision-making)?

Table 9. List of topics that are wished to be found in the PED database.

Category	Comments
Lessons learned	Special reference to real life implementation
Results	Data analysis and potential research on the field
	Metadata as the useful information that can the real goal of consultation
	Benchmarking to compare PEDs
	Need to normalize results depending on a number of factors (size, location. . .) to really compare different initiatives
	Privacy and data protection
Sets of technologies and solutions	-
Economic parameters	As a way to benchmark the different PED technologies
Citizen engagement	Energy poverty
	Prosumers
	From engagement to empowerment
Definition and boundaries	Need to standardize and have a reference framework to establish the energy balance
Contact persons	It is very valuable to have a contact address to ask more about the initiative
Regulatory framework	Drivers and Enablers

The PED DB tool, as well as other related PED-based tools, can be deployed by decision-makers for collecting static information for dynamic decision-making processes, including comparing and benchmarking features of the PED initiatives and how these may be transferred to other cities.

The decision-making process always has a dynamic characteristic, since the evaluation and assessment of the impacts of the interventions (beforehand) require the multi-criteria analysis of social, cultural, economic, political and legal aspects. The feedback from the workshop participants can be divided into three different clusters of interest: features of the database, parameters and information to be collected, and next steps and future work.

Several responses arose regarding the features to be added to the database. Some of these features, such as mapping information and filtering with a few parameters, have already been applied in the frontend interface of the PED DB. On the other hand, clustering the options, grouping different cases into characteristics, and benchmarking with different cases may also be counted among the most-mentioned comments. Among these answers, one suggestion for benchmarking the success of the case studies (whether a scale for that is possible) was very interesting. Maybe a scale could be generated to assign a label for each PED case study or PED-relevant case study to standardize the processes for becoming a PED.

Among the most suggested parameters to map in the database, the following ones were noted—building uses, energy balance calculations, carbon footprint, project areas, developments, and characteristics—as already defined parameters. It was also often suggested to include development barriers, success factors, experiences from different projects, energy parameters and technologies, and motivations for PED developments as further database parameters. Climate vulnerability can be counted as a compelling suggested parameter to be directed to the case studies. Climate zones are already added to the cases, but the vulnerability of the climate contexts and how to overcome the disadvantages may be included as open questions in the database. Energy poverty reduction indicators can also be a good option to understand the social perspective of the case study.

The discussion of next steps for the evolution of the PED DB tool included how to encourage decision-makers to plan and implement PEDs from a researcher's point of view. In the session, a few people highlighted the importance of learning from each other.

The case studies will be compiled by the researchers or municipalities directly, but the citizens/inhabitant points of view/social responses are also very important to motivate PED implementations. For this reason, a participatory approach should also be followed to introduce the PED DB and to include discussions of parameters. Aligned with this idea, new stakeholder workshops may be organized in the future for knowledge development and to propose a participatory mapping of the database.

The interactive usage of the database between researchers/experts/practitioners and municipalities may also be integrated into the system. Sometimes, the experts are consultants for the decision-makers, and the former can translate the language of the database f the latter. For this reason, an interface facilitating the discussion environment for each case study may also be an option for the future. However, the database tool also comes with some challenges. It can be problematic to keep the database up to date, and over time, it might be difficult to keep contributors motivated to add new information to the database. As the database is a collection of cases from different parts of the world, the language barrier might be an additional challenge for keeping the database unified and complete. For this reason, local experts should be engaged.

4. Conclusions

The experience of the workshop held during the SSPCR 2022 Conference in Bolzano, organized in the form of World Café, offers the conclusion that the effective enrolment of stakeholders is crucial for the successful design and implementation of projects related to PEDs.

During the workshop, four tables were formed, one for each IEA EBC Annex 83 Subtask (ST-A Definitions and context, ST-B Methods, Tools and Technologies for Realizing Positive Energy Districts, ST-C Organizing principles and impact assessment, ST-D Demos, implementation and dissemination). Twelve questions were raised to the stakeholders—three for each subtask—that covered the main activities of each subtask.

Stakeholders discussed the necessity to characterize PED DNAs, including morphologic, socio-economic and demographic characteristics, as well as technology components (in the same categories), characteristics that ensure a quality of life, and other aspects (like challenges or barriers). All these characteristics can help in building PED archetypes and analyzing future patterns. Such an approach can also ensure transparency and allow different PED areas to be comparable. The stakeholder's involvement, targets, barriers and challenges could inspire other stakeholders for replication purposes. The business model aspect was highlighted as an enabler of PED implementation, which is an aspect that might be missing in the PED DNAs and should be studied further. To describe the business model–stakeholder relationships, value proposition or costs and revenue streams could be included. The latter aspects could help policy-makers in building stronger business cases and untapping new investments. Common barriers typically found in cities are further explored in Section 3.3.

Regarding the tangible aspects of quality categories, as well as technology identification (Section 3.3), access to soft-mobility services, nature solutions and social participation are highlighted. Also, the exploration of other quality indicators such as comfort, security, safety, aesthetics, affordability, inclusion, literacy, and transparency were investigated, which could be relevant for PED development. These features match perfectly with the values promoted by the EU New European Bauhaus and are common keywords found in their databases [76–80], which puts sustainability, inclusivity and beauty at the heart of the projects for improving the quality of people's lives. Although these aspects can be tangible, like infrastructures or aspects that can be measured by the perception of the citizens and stakeholders involved in the PED, the respective indicators are difficult to obtain and standardize. Similar issues can occur with the intangible aspects.

Regarding technologies, energy efficiency, renewable energy technologies (or low-carbon technologies), energy flexibility, and sustainable mobility were highlighted. The more detail that is given in the PED DNA section about these technologies, the greater the understanding of the energy system of the PED that can be achieved.

Bundling these solutions with enablers, such as financing instruments, social innovation or innovative governance, can help overcome some of the challenges and barriers found. However, as highlighted by stakeholders, a lack of standardization of the concept of PEDs increases the investment risks and a supportive environment (e.g., lack of regulation, specific subsidies or targets). It also creates social challenges, like social acceptance. The aspect of data is also a topic that impacts significantly PED development, as the more data there are about PED development, the better understanding of the benefits and drawbacks that can be obtained. Lastly, business models to ensure long-term viability are seen as a must for facilitating a widespread adoption of PEDs.

Modeling plays a crucial role in the context of Positive Energy Districts (PEDs), by providing comprehensive outputs for various stakeholders. It enhances the efficiency and economic benefits of district energy systems through simulation and optimization tools. The specific objectives of the model vary, from public education to city-level decision-making and research to further improve technology. Also, data-driven approaches like digital twins are gaining significance for real-time system monitoring and control.

To capture KPIs in the models, it is possible to establish a connection between the models and various characteristics highlighted in Section 3.1, such as morphologic, socio-economic, and demographic factors, technology components, and quality-of-life aspects for informed city-level decision-making. In addition, an inclusive system modeling approach considering various elements of PEDs can increase public awareness and help the energy transition process. This integration, also, serves multiple purposes: it could enhance the understanding of the energy system within PEDs, facilitate the creation of PED archetypes that can be compared and replicated in different urban zones, and ensure transparency and comparability among various PED areas, inspiring stakeholders for further implementation.

Furthermore, as this paper explores the specifics of technologies, such as energy efficiency, renewable energy, energy flexibility, and sustainable mobility, energy models can gain deeper insights into the dynamics of the energy system. Combining these solutions with enablers such as financing instruments, social innovation, and innovative governance will help in addressing the challenges and barriers identified for the PED development and diffusion. This approach will further contribute to the overall success and viability of PED implementation, such as the use of a holistic framework that integrates economic, environmental and social aspects in the design and implementation of PEDs.

The discussion highlighted the cross-disciplinary collaboration among researchers, policymakers, and industries, as well as municipalities and citizens, as auspicial. Another important aspect is the need for replicable and standardized approaches for assessing the environmental and economic impacts of PEDs, in which the social aspects are included, especially with regard to energy poverty reduction, affordability, accessibility to local services, social participation and human well-being.

In addition, the social aspects of living in a PED should be addressed in the same way as the energy aspects, since they are closely related, and possible benefits in one area have a positive impact on others (e.g., the exploitation of renewable sources of energy leads to a decrease in the concentration of pollutants).

The engagement of stakeholders and specific information and dissemination campaigns must be conducted, highlighting the potential benefits for each category of stakeholder.

Moreover, the main tools and guidelines for PED implementation were explored. Regarding the need for development of design guidelines for Positive Energy Districts, the participants of the workshop identified key topics needed in PED guidelines, including, among others, the strategies and the uncertainties related to the PED definition. Regarding the tools, a PED database (PED DB) developed under IEA EBC Annex 83 was provided to the workshop participants, who gave suggestions on what should be included within the PED DB (including the lessons learned from real-life implementations and the benchmarking for comparing PEDs). As the PED database is meant to be accessed by different stakeholder groups, there are many potential applications to be considered. Urban planners and developers could use it for designing new districts or retrofitting existing ones, as well as for simulating various development scenarios in regard to energy production, consumption and environmental impact. PED DB could be used for energy management and monitoring, as well as for policy-making and monitoring. It could also be a useful tool for researchers and in wider academia for educational purposes, and for developing new methods and technologies by analyzing collected data. The PED database can also support community engagement and increase public awareness on a district's energy performance and sustainability efforts. Technology companies could integrate PED database into smart systems and IoT solutions for better performances and for optimizing energy distribution and consumption.

Finally, it is possible to highlight, as the most relevant priorities within PED diffusion and development, the following listed issues: data analysis and integration, digital twins of districts and cities, proper stakeholder involvement in the design process, integrated sustainability approaches, and innovative business models to push the market integration of technologies and PED solutions, as well as the development of PED certification schemes. These aspects certainly need to be further and carefully investigated in the next few years.

All the findings reported in this paper point towards clear research needs and further development necessities highlighted by stakeholders, policy-makers, academics, and urban planners. This can allow for the identification of more efficient and needed policies in supporting the development of Positive Energy Districts, recognizing priorities from technological and social perspectives. The results proposed in this paper could suggest that urban planners should embrace more integrated and holistic approaches in city developments. This will also help local administrations develop living laboratories, in addition to fostering the social inclusion of all community members.

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