designs

MDPI

Review

Positive Energy District Success Factors: Learning from Global Challenges and Success Stories

Dimitrios Siakas [1], Kerstin Siakas [2,3,*] and Georgios Lampropoulos [4,5,*]

1 Sustainable Energy Systems Research Unit, HAMK Tech, Häme University of Applied Sciences, 13100 Hämeenlinna, Finland; dimi.siakas@hamk.fi
2 Department of Industrial Production, School of Technology and Innovations, University of Vaasa, 65200 Vaasa, Finland
3 Department of Information and Electronic Engineering, School of Engineering, International Hellenic University, 57400 Thessaloniki, Greece
4 Department of Applied Informatics, School of Information Sciences, University of Macedonia, 54636 Thessaloniki, Greece
5 Department of Education, School of Education, University of Nicosia, Nicosia 2417, Cyprus
* Correspondence: ksiakas@gmail.com (K.S.); lamprop.geo@gmail.com (G.L.)

Abstract

The aim of this study is to examine existing positive energy district (PED) initiatives by using an explanatory research approach for gaining insight, identifying patterns, clarifying underlying processes, exploring cause-and-effect relationships, and explaining phenomena in a greater depth. Specifically, studies from the existing literature that have explored multiple PEDs were analyzed. Current challenges, barriers, and obstacles, as well as success factors, good practices, and policy guidelines are thoroughly investigated, evaluated, categorized and compared to unveil lessons learnt from diverse existing international projects for turning urban areas into self-sustainable and greener urban neighborhoods. The proposed framework aims to reveal the required processes for successful PED creation and operation. It provides an overview of the current state of the art and enhances comprehension and know-how about the processes needed for the successful adoption and integration of PEDs based on lessons learnt from global challenges and success stories.

Keywords: positive energy district; renewable energy; urban energy systems; energy efficiency

Academic Editors: Tony Castillo-Calzadilla, Carlos Quesada Granja and Xiaohu Yang

Received: 31 July 2025
Revised: 11 September 2025
Accepted: 17 September 2025
Published: 19 September 2025

Citation: Siakas, D.; Siakas, K.; Lampropoulos, G. Positive Energy District Success Factors: Learning from Global Challenges and Success Stories. *Designs* **2025**, *9*, 111. https://doi.org/10.3390/designs9050111

1. Introduction

According to the United Nations (UN), urban cities are predicted to cover 70% of the worldwide population in 2050 and to contribute to approximately 78% of global energy use and consumption [1]. Furthermore, urban cities account for 60% of greenhouse gas (GHG) emissions. Global warming, a result of GHG emissions, continuously causes changes to the climate, which is why reducing GHG emissions globally is an important and urgent matter. This significantly concerns decision makers, leaders and energy providers. From a European Union (EU) point of view, the EU strives to become climate-neutral by 2050 [2], meaning an economy where anthropogenic GHG emissions and their removals are in balance over a given period.

The EU Directive 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) [3] indicates that the EU, including all its member states, aims to accomplish net zero GHG emissions, entailing a balance between emitted and absorbed atmospheric GHGs. Other legislative frameworks to support member states in reaching the EU targets are the Revised Renewable Energy Directive EU/2023/2413 [4], the Electricity Directive [5], Effort Sharing Regulation [6], the Energy Efficiency Directive [7], and the EU Emissions Trading System [8].

1.1. Creation and Operation of Positive Energy Districts

Sustainable energy refers to "energy resources that can fulfill existing energy requirements while preserving the capacity of future generations to meet their own energy needs" [9] and is highly interconnected with many of the sustainable development goals (SDG) of the UN [10]. In this context, the building energy sector plays a vital role in reducing global warming and in advancing intelligent buildings, intelligent cities, and intelligent regions to stay up-to-date and competitive [11,12] while capitalizing on renewable energy resources [13] and the context in general, e.g., geothermal energy.

The growth of renewable energy sources, distributed energy resources, smart grids, and prosumer engagement, has added complexity and created new challenges regarding the energy supply balance and stability of the overall energy system [14]. In regard to the EU 2050 aim, a joint initiative between the SET Plan and Joint Programming Initiative Urban Europe was created [15] and an Implementation Working Group handling Positive Energy Districts (PEDs) for sustainable urban development was established in Autumn 2018. A target of initiating 100 EU PEDs by 2025 was set [16]. PEDs, also known as "energy-efficient neighborhoods and energy-positive neighborhoods", are system-level concepts with local management of energy sources. The PED locally stores the surplus energy or exports it to the overlaid grid and buys energy from the grid when there is a shortage at the local level [14]. The definition of PEDs is that "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" [17]. The PED concept is based on earlier ideas of single nearly/net/positive zero energy buildings, extended with energy mutuality between urban decarbonization and buildings [18]. The concept of PEDs aims to deliver environmental, economic, and social benefits through the optimization of local energy systems. PEDs constitute an innovative concept with challenging adoption and implementation. Data from existing PED projects aiming toward effective energy transition and sustainable urbanization a across Europe has been collected by JPI Urban Europe [19].

Through the "Clean energy for all Europeans package" [20], which was implemented in 2019, the EU introduced the concept of energy communities (EC) in its legislation. The aims were to empower citizens to drive the energy transition locally to benefit from advantages such as improved energy efficiency, reduced energy poverty, lower bills, and prospects for green local jobs [20]. The idea was that citizens would aid in improving the public acceptance of renewable energy projects as well as facilitating private investments and the restructuring of energy systems. In 2022, however, over 41 million EU citizens were unable to warm/cool their homes adequately [21]. Energy poverty is a multi-faceted phenomenon caused by low income, high energy expenses, and poor building energy efficiency. Hearn [22] interviewed 20 stakeholders who were directly involved in managing the development of PEDs, smart cities, or carbon-neutral districts, many of whom held multiple roles. They noticed that stakeholders recognize significant potential in PEDs for reducing energy vulnerability. Recognizing the potential contribution of ECs in realizing an affordable, secure, and cleaner energy system, the REPowerEU Plan [23] proposed the political objective of, by 2025, attaining one EC per municipality with a population of higher than 10,000. The EC goes hand in hand with PEDS.

PEDs are flexible and efficient energy areas and require the integration of different energy systems (electricity, heating, cooling, energy storage) and interaction among users, buildings, regional energy systems, transport, and information and communication technologies (ICT) systems. Energy-positive areas can be of many types and consist of many different actors. Most existing PED projects (66%) connect newly built neighborhoods to existing ones [24]. Technological limitations, complex ownership structures, building protections, and the preservation of cityscape may present challenges in implementing a PED, particularly in existing urban structures. However, approximately 75% of the building stock in the EU is energy inefficient [25], which make integrating and applying PED solutions to the existing urban structure a priority. Terés-Zubiaga et al. [26] consider that an efficient way to accelerate the reduction of energy consumption in the building sector is by increasing renovation rates at the district level, which involves upgrading multiple buildings within the same area.

An 8-step process of PED development was proposed by the Joint Research Centre report, that is, "the science and knowledge service of the European Commission" [27]. The report claims that the positive impacts of PEDs principally include a reduction in the EU carbon footprint and the empowerment of citizens and stakeholders to take the lead in their own communities. The report also states that the PED approach is complex due to the potentially high number of technological combinations at the district level. In order to facilitate PED, the local management system needs to utilize innovative ICT and autonomous cyber–physical systems (CPSs) for addressing the processes of controlling, managing, monitoring, and optimizing energy generation, consumption, and trading [28]. CPSs form part of the basic frameworks for the creation of smart and autonomous systems [29,30]. They enable, through multiple synchronous applications over diverse network structures, continuous communication and data analysis among physical devices, cyber platforms, and digital infrastructures [29,30]. Developments in computer science, electronics, and robotics drive the advancement of automated sensing systems, reducing the limitations of manual data collection. CPSs are being applied in the development of different smart applications, such as smart buildings, smart cities, smart transport, smart grids and utility systems, etc.

1.2. Achieving Positive Energy District Goals

In the 2010s, the European concept of smart cities put an emphasis on sustainable urban environments that utilized smart technologies integrating data and sensors collecting information from the surrounding environment. A minimum level of artificial intelligence is fundamentally incorporated into the smart innovative technologies [31]. Whilst smart home concepts aid end-users in comprehending their energy use, the concept of PEDs aims to reduce energy consumption and locally produce more energy than is consumed on an annual basis [32]. The PED concept originates in nearly zero-energy buildings and zero-energy buildings (ZEBs), which introduce an integrated approach to energy efficiency, emphasizing the utilization of renewable energy sources [27]. Urban development is transitioning from building solutions toward advanced PEDs with the aim of accelerating the transition of clean energy for achieving the EU's climate and energy targets to a district level [33].

The integration of different ICT and CPS tools is significant to develop smart cities and PEDs. Progress in computer science, electronics, and robotics impels the development of automated and autonomous sensing systems, which ensure consistency and enable the optimization of processes, minimization of human intervention, and facilitation of remote surveillance [34]. Digital predictive technologies that use analytical approaches to identify patterns and trends for predicting future events and outcomes are significant tools for adhering to the targets of ZEBs and PEDs. Together with sensor-based control systems, which activate diverse functions based on the detection of changes in the environment, ZEB policies for buildings and PEDs are supported [35]. Interactions between humans, infrastructures, and technologies are increasing; hence, there is an emphasis on human-centric PED designs [36]. Buildings, cities, and regions are utilizing technological improvements, aiming for smarter performances and improved sustainability. This phenomenon is called the urban intelligence concept [35]. Future cities will progressively be managed through smart city solutions that consider the efficiency of water and energy consumption, waste management, and reducing noise, pollution, and traffic congestion. Energy consumption is the main concern of PEDs.

The three Ds, namely decarbonization, decentralization, and digitalization, are the solutions proposed to meet the increased energy demand caused by urbanization, low-carbon policy requirements, and a transactive energy market [37].

Decarbonization: The EU goals of climate-neutrality by 2050 are in harmony with the decarbonization goal of developing smart CPS distribution systems that promote energy efficiency, local energy accommodation, and energy transmission flexibility [38].

Decentralization: An increasing number of distributed energy resources are nowadays integrated into the distribution system. Such DERs are building PV systems, electric vehicles, and distributed energy storage. Consumers represent a significant component of any smart energy system. In emerging distribution systems, electricity consumers are going to be more actively involved in decisions regarding energy, including home energy management and participation in peer-to-peer markets [39]. Since human behavior is important in PEDs, emphasis toward cyber–physical–social distribution systems should be considered [40].

Digitalization: To achieve real-time monitoring and control, smart devices are installed in a distributed manner. These devices include control mechanisms, communication, and a big collection of data. They are connected to each other or to the control center via a computer network by wired or wireless communication techniques. This type of digitalization through distribution systems describes CPSs [38].

1.3. Research Question, Aims of This Study

The research question of this study is as follows: What lessons can be applied from diverse existing international projects regarding the transformation of neighborhoods into new self-sustainable, positive and greener urban areas? To answer the research question, a critical examination of existing PED initiatives, their success stories, good practices, lessons learnt, and policy guidelines, together with challenges and obstacles, needs to be carried out. This study aims to expand the current understanding of PEDs by thoroughly examining, identifying, categorizing, evaluating, comparing, and presenting earlier research findings in a structured way enriched with reasoning regarding the results. The ultimate aim is to enhance comprehension and know-how about the creation and operation of PEDs and to contribute to further development and research in this important domain.

1.4. Structure of This Article

The structure of this article is as follows: Section 2 describes the research method. In Section 3, the analysis of experiences from existing PEDs is presented. This analysis forms the basis of the PED Success Factor framework. The analysis is based on insights from studies that examined multiple PED projects. In Section 4, the PED Success Factor frame-work is presented. In Section 5, the related outcomes are further discussed, and in Section 6 the conclusions of the study and future research directions are presented.

2. Method

The explanatory research method was used in this study for exploring cause-and-effect relationships, understanding underlying processes, and explaining phenomena in more depth. This method supports researchers in gaining valuable insights into a topic, clarifying concepts, and identifying patterns, before conducting more conclusive and structured research. Opposed to descriptive research, that only describes phenomena, explanatory research seeks to answer questions such as "Why does this happen?" and "What factors influence this outcome?" Skinner et al. [41] argue that explanatory studies are trying to answer two questions, namely "What are the causes of normative and differential patterns of development as they unfold in the actual contexts of daily life?" and "What are the mechanisms by which those causes exert their effects in shaping development?" The aims of this explanatory study are to gain insights into what factors are important for successful PED implementation and operation.

A systematic literature review following suitable approaches, such as the PRISMA guidelines, is often regarded as a valid method for identifying and collecting related documents, but a broad and wide-ranging topic, such as PED challenges and success stories, requires a broader perspective and more flexible approaches [42]. Hence, although this can be regarded as a limitation of the study, a systematic literature review approach was not adopted.

A typical explanatory research method inevitably includes a literature review for reviewing existing information in order to identify gaps or trends, seek new insights, and evaluate phenomena from a different point of view. The overview on PED experiences, such as drivers, success factors, challenges, and barriers, involves investigating various scientific articles published in journals and conferences. As this study covers a wide-ranging, complex, and interdisciplinary topic, a comprehensive critical literature review, following suitable guidelines [43], was performed by searching for suitable scientific articles in well-known library repositories, such as "Web of Science", "Scopus", "ACM", "IEEE", and "Google Scholar", using suitable keywords, such as "drivers", "experiences", "success factors", "challenges", "barriers", "positive energy districts", and "PED" to identify relevant documents that were then further processed and to critically analyze prior research without bias.

This study strives to present a comprehensive collection of fundamental PED success factors and to propose a suitable framework with the aim of improving the understanding of critical aspects in the creation of PED projects. To narrow the research scope, this study applies an explanatory research approach by exploring why something happens (the creation of PEDs), explaining the causes (minimizing global warming) and consequences (challenges and success factors).

Therefore, this study put emphasis on identifying studies within the literature that explored the processes and outcomes of multiple PED projects. Hence, this study focuses on expanding the existing understanding of PEDs by examining real-life PED experiences of multiple projects to identify key success factors. These factors were further examined, which led to the creation of the PED Success Factor framework. The framework highlights key aspects and processes that need to be created and nurtured throughout the different stages (e.g., initiation, planning, prototyping, execution/implementation, evaluation, etc.) of the PED lifecycle. The process of mapping is important to understand and improve operations by visualizing workflows, identifying inefficiencies, and promoting communication and collaboration. Specifically, it improves the understanding of how work is performed, locates areas for improvement, and standardizes processes for increased efficiency and compliance. It also ensures a more all-inclusive identification of stakeholders, capturing the dynamic nature of their emergence, changes in relative importance, and withdrawal [44].

3. Experiences from Existing PEDs

3.1. First Study—Analysis of 62 PEDs

Saheb et al. [45] revealed findings from 62 pioneering PEDs identified in EU project databases, such as Intelligent Energy Europe, CONCERTO, FP7, Covenant of Mayors. The drivers they distinguished for utilizing PED approaches (in addition to contributing to combating against global warming) were motivated by urban renewal and the conversion of industrial or brownfield areas into residential or mixed communities. They emphasize that "from a policy perspective, the concept of a zero-energy community has proven to be hard to implement and evaluate" despite the fact that there is evidence for "the feasibility of the zero-energy concept for individual buildings". They emphasized the lack of consistent terminology and targets used when implementing 'zero energy communities', which makes it difficult for policymakers and academics to carry out independent assessment. They identified a hierarchical approach that enabled decision makers to adapt to the specific challenges and opportunities of the local context. In our opinion, a democratic approach would be preferable since stakeholder commitment is required and in a hierarchical structure full commitment might be difficult. Moreover, they identified that cross-sectoral planning is beneficial because in addition to energy issues, it might include other fields like waste or water optimization. To improve citizen commitment, they identified capacity building and training of municipalities and citizens as a way to enable their complete and effective participation. They also emphasize that the adequate documentation and monitoring of projects aims to offer a solid evidence base regarding what went well/did not go well and mistakes and is significant for future PED development.

By analyzing the outcomes of Saheb et al. [45], some key aspects that lead to successful PED development, adoption, and integration were identified, as presented in Table 1 and further discussed and analyzed.

Table 1. Key aspects in developing effective PEDs.

Key Aspects in Developing Effective PEDs Based on Saheb et al. [45]	Analysis and Comments
"Clearly defined long-term targets, community boundaries and values to support citizen engagement"	The deep-rooted values and interests of individual societies display divergence of values, having an impact on business models, governance structures, decision making, knowledge sharing, social acceptance, etc., [46]. Therefore, it is of utmost importance that targets, community boundaries, and values are discussed, aligned and clearly defined by stakeholder collaboration from the very beginning. The value that each strategic initiative is expected to create for the different stakeholders also needs to be discussed and elaborated on. In particular, citizen engagement is considered important in PEDs [47], and to make an impact it needs to be embedded in every stage of the decision-making process. Involving citizens is considered important in PEDs, as they undertake an integral role in defining themes, finding solutions, and identifying priorities for action [48]. Citizen involvement is, however, voluntary, and it requires deep commitment, proper allocated time, and an interest in co-creation.

Table 1. *Cont.*

Key Aspects in Developing Effective PEDs Based on Saheb et al. [45]	Analysis and Comments
"Linking targets to community priorities such as economic development, urban renewal, energy poverty, energy security (especially for isolated communities)"	In order to obtain political-level and municipal commitment and financial support, it is significant to align PED targets with municipal priorities. After identifying municipal priorities and having decided on strategic initiatives, effective communication is needed so that all involved stakeholders understand and agree on the initiatives. Strategic project management improves decision making, project performance, and competitiveness [22]. Strategic planning forms the path to follow, but smooth alignment with project execution may be difficult if all stakeholders are not onboard, giving rise to inadequate alignment that causes inefficiency, and may not bring expected results. Hearn [22] emphasizes that stakeholders perceive the reduction of energy poverty as having significant potential in PEDs and highlights that PED replication should, in addition to decarbonization, also address energy poverty mitigation.
"Transposing long-term goals into milestones and short-term objectives to avoid discouraging the community"	PED implementation necessitates a profound understanding and consideration of policies, priorities, strategies, resources, solutions, and contextual conditions [11]. In strategic management, the vision refers to mental images of the future (zero-energy communities), which become tangible in the form of mission statements (100 PEDs by 2025), a definition of the primary purpose that articulates the responsibilities the stakeholders (distributed decision-making and stakeholder commitment). The goals are attempts to improve performance by making mission statements more concrete. Objectives represent the operational definitions of goals in more precise terms and describe what needs to be accomplished in order to reach the goals. A significant factor that was identified in the four projects was to divide long-term goals into short-term objectives and to use milestones. Balancing a long-term vision with short-term milestones is critical for stakeholder commitment and effective productivity.
"Measurable targets and a clear implementation timeline"	An effective implementation plan with measurable targets and a clear implementation timeline provides a feasible roadmap for project execution. It outlines key elements to guide the PED project toward successful project completion and goal achievement. The foundation of the implementation plan relies on a well-defined project scope and clear goals. Cai and Gou [49] proposed a set of performance indicators (KPIs) based on the KPIs of existing positive energy buildings (PEB), including the geometric data of the building and energy-related indicators, such as the power of the PVs and the area of the PVs deployed. Similarly, Barrutieta et al. [50] looked at building geometry, location, energy consumption, and building-integrated photovoltaics and their interrelations to create PED KPIs. Both studies emphasize that balance assessment KPIs can include a renewable energy supply compared to energy demand or annual energy exchanges with the grid. The Smart Readiness Indicator (SRI) has recently also emerged as a promising KPI aimed at energy savings and assessment of the ability of buildings to respond to user needs and energy flexibility. SRI evaluates the capability of a building to integrate future emerging technologies and adapt to occupant requirements regarding the functionality levels of various smart services [51].

Table 1. *Cont.*

Key Aspects in Developing Effective PEDs Based on Saheb et al. [45]	Analysis and Comments
"Transparency about progress toward these targets and any revisions or trade-offs made during project implementation"	Transparency and inclusiveness toward KPI targets are essential for tracking progress, making well-informed decisions, and driving success. A communication strategy considering KPI transparency creates alignment, trust, and engagement. Innovation is underpinned by the concepts of invention (creation of a new idea or concept) and creativity (the act of turning new and imaginative ideas into reality). Stakeholder engagement is a key driver of PED value, enabling, inclusive, effective, and sustainable energy solutions. Engaging stakeholders, in particular citizens, enhances co-creation, aligns interests, and supports the successful planning, implementation, and long-term sustainability of PEDs. It maintains that PEDs are not only technically effective but also socially accepted. The emphasis is on optimizing the value of the project and innovation for diverse stakeholders (society, community, institutions, and individuals) and boosting its impact [52].
"The supply and demand of urban services (energy, waste, water and transport) needs to achieve integration at a local level"	A strong awareness exists regarding increased well-being of people as a result of accessibility to services and amenities provided in urban areas and, as a consequence, the management of these services is a prior concern for both citizens and PED planners. A PED performance-based planning approach is built around urban ecosystem services, such as energy, waste, water and transport [53]. The type of performance, for example, what kind of ecosystem services should be targeted, depends on service demand of the ecosystem, and the level of performance depends on the impacts on ecosystem service supply [54].
"The local residents and community need to be meaningfully engaged"	Local residents' active participation is not only beneficial but essential for successful PED development. It ensures that the development process is inclusive, sustainable, and reflective of the needs and aspirations of the PED. PEDs need citizens who are users, producers, consumers, and owners, in addition to political actors. A combined effort from these actors may have a significant impact on PEDs, driving the climate transition, preserving the environment, and advancing the economy [47].

Furthermore, some key challenges were also identified based on the analysis of Saheb et al. [45]. These challenges are presented and further analyzed in Table 2.

Table 2. Key challenges in developing effective PEDs.

Key Challenges in Developing Effective PEDs Based on Saheb et al. [45]	Analysis and Comments
"Lack of agreement regarding the definition of a zero-energy community, its boundaries and which urban services are included in it"	Kozlowska et al. [18] highlighted the need for a clear and comprehensive PED definition, and the agreement of a coherent PED design approach. In order to find an adequate balance between different energy sources in a PED, it is imperative to identify which renewable energy resources are suitable in the climate zone of the PED, which specific needs and ambitions they represent, and what different functions and guiding principles need to be optimized against each other [55]. When developing PEDs, the specific situation of the urban context should be considered, such as density, type of buildings, available local renewable energy resources, etc. Most projects take different pathways due to local circumstances regarding energy sufficiency measures, use of renewable energy produced locally or nearby, and use of technologies for minimizing energy needs. Also, the level and kind of local integration of supply and demand of urban services play an important role.

Table 2. *Cont.*

Key Challenges in Developing Effective PEDs Based on Saheb et al. [45]	Analysis and Comments
"Replication difficult because the geographic, political, economic, historical, and social context of urban areas differ significantly"	Across different countries, cities, or districts, standardized PED solutions are difficult to apply because they are content-specific both regarding existing values [55,56] and also because of their spatial and morphologic differences [18,57]. The identification of common PED characteristics was proposed for the creation of generic PED archetypes [18]. Key PED characteristics were grouped into the following: (1) facts and figures (built form, climate, density, energy demand, land use, renewable energy potential, physical geographical location, sizes/population size); (2) technologies (energy distribution (e.g., co-generation, district network), energy-efficiency measures, energy storage, mobility solutions, renewable energy supplies); (3) quality of life (accessibility to green space, accessibility to services (e.g., bike lane, public transportation)), health impacts (e.g., air pollution, noise pollution), local value/sense of community, social-economic conditions, user comfort; and (4) other (impacts of PEDs, local challenges, local targets and ambitions, regulations/policies, stakeholder involvement.
"Governance and citizen engagement"	Energy citizenship denotes active participation in energy systems and engagement in energy-related discourse through conscious decisions related to energy [58,59]. The analysis approach, a combination of citizenship critical social psychology and governmentality (a society where members play an active role in their own self-government), reveals neoliberal energy citizenship (free-market capitalism, reduction in government spending and deregulation) as the dominant social representation. It identifies unrestricted representations of energy citizenship grounded in entrepreneurial energy engagement at a local level. The image of an ethical PED prosumer has been argued to exclude information for illiterate people to become prosumers [60] because of their lack of energy awareness and energy action. Focusing on local and human rights claims, the analysis of Nguyen and Batel [58] also revealed the following two types of energy citizenship, namely the "active vs. vulnerable consumer" (at national policy level tackling existing and future energy poverty) and the "local–global citizen" (tackling global climate matters by local energy actions).

3.2. Second Study—Insights from 61 PEDs

The insights from 61 PED projects were presented by Bossi et al. [24] following the analysis of the JPI Urban Europe booklet [19] for identifying common characteristics to advise and guide PED stakeholders. Further, 29 cases of the total 61 cases outlined in the booklet reported a PED ambition. Bossi et al. [24] found that there is a geographic imbalance between PED/toward-PED projects, most of them being in Norway (eight) and only two in Eastern and Southeastern Europe, which they attribute to the existence of particular matters or national programs that focus on PEDs.

In 2020, the majority of the PED projects were in the stage of implementation (69%); 24% were in the stage of planning and only a few in the stage of realization (3%) or in operation (3%) [24]. Toward-PED projects were in their implementation stage (44%); 13% were in the planning stage and realized (9%) or in operation (31%). By analyzing the building structures, they were grouped into "Newly Built", "Existing Neighborhood", and "Mixed".

In total, 66% of the projects with PED ambition were a mixed type of neighborhood with both newly built and existing buildings and infrastructures, 28% were newly built districts, and 7% were existing neighborhoods. Totally, 41% of the toward-PED projects were based on existing neighborhoods, 38% on mixed type, and 16% were newly built.

A common PED approach seemed to be to combine a high number of energies. Totally, 29% of the PED projects used "moderate mixed" (2–3) energy sources, 50% used "highly mixed" (4–5) energy sources, and 13% "very highly mixed". Only 8% of the PEDs used a single source of energy. Totally, 60% of the toward-PED projects were "moderate mixed", 30% were "highly mixed", 7% used only a single source, and only 3% used "very highly mixed" energy typologies. Hence, we see that PEDs use more energy sources (4–5) than toward-PEDs (2–3) for reaching the required energy surplus from renewable energy sources. The preferred types of energies were district and local heating, photovoltaic, heat pump systems, and geothermal energy [24].

Bossi et al. [24] summarize that the PED main success factors are as follows: "Stakeholders; citizen involvement strategies, integrated technology and political support". Siakas et al. [46] also studied the JPI Urban Europe booklet and carried out a thematic analysis for categorizing, extracting, and synthesizing texts. The data were examined to identify common themes and topics, ideas and patterns of meaning that were expressed repeatedly. The success factors they identified included early and broad stakeholder involvement, interdisciplinary collaboration, and context-sensitive planning for addressing local needs and avoiding unintentional consequences (i.e., gentrification, inequality). They also recognized that enabling policies and financing instruments are significant for supporting innovation, and scaling and replicating PEDs in diverse urban settings. However, for replicating successful PED models, culture is a decisive factor that needs particular attention. A socio-cultural, technological, economic, environmental, political, legal, ethical, and demographic (STEEPLED) factor analysis [46] was proposed for a more complete assessment including multiple aspects. Interdependencies between technology, governance, and market dynamics characterize PEDs. Emerging contemporary technologies considered important for the creation and operation of PEDs, such as cyber–physical systems, CPS, Digital Twins (DT), artificial intelligence, Internet of Things, edge computing, and Blockchain technology, are integrated and intertwined in different ways. A holistic, cross-disciplinary, and systematic understanding is crucial for managing complexities and urban challenges.

The primary PED barriers are "access to adequate funding and business models". In comparison to traditional projects, PED projects are more expensive and complicated. Hence, there is a need to adopt and apply advanced business models and obtain multiple financial sources. Flexible regulations and a devoted legal framework are required for meeting the new challenges. Based on the work of Bossi et al. [24], key areas to be examined were identified, which are presented and further discussed in Table 3.

Table 3. Key areas to be examined.

Key Areas to Be Examined Based on Bossi et al. [24]	Analysis and Comments
"Using PED Labs for testing, experimenting with different approaches and strategies, elaborating with guidelines and tools and monitoring of existing approaches."	A living lab is an open innovation ecosystem where new ideas and solutions are developed and tested in a real-world context. Open innovation is a tool for integrating customers/end-users in the innovation process, particularly in the ideation stage of innovation, where the voice of the customer is crucial for later customer acceptance due to a feeling of participation and influence on the process/product [61]. A living lab is an excellent place for developing and testing innovative ideas in real life. In a living lab, end-users provide feedback at each stage of the iterative process. The continuous feedback enables adaptation and improvement of the innovations to meet end-user needs and requirements. PED projects usually create living labs across all countries of the project aiming to pilot real-world solutions for more inclusive, affordable, and sustainable energy systems.

Table 3. *Cont.*

Key Areas to Be Examined Based on Bossi et al. [24]	Analysis and Comments
"Developing appropriate governance structures and adaption of the legal framework to fit PEDs consideration of functional urban areas (regional perspective); Collaboration within and between stakeholders, such as city administrations, civic society, energy providers, real estate industry etc."	Governance structures enabling policy and planning integration at both the vertical and horizontal level are crucial for allowing multi-level coordination at the EU level, national level, regional level, and local level. Public and private partnerships involving local authorities, energy providers, real estate developers, and citizen groups develop shared ownership and investment constructs that foster accountability. In particular, citizen support is needed for urban transformation solutions [47]. Smart integration and cross-sectoral collaboration between energy, transport, construction, water, and waste sectors are desirable features that will add value to the creation and operation of a PED.
"Incorporating of PED strategies into a comprehensive urban planning: mainstreaming of energy planning in urban planning strategies; connecting energy aspects with climate action; adapting high-quality regarding functions and design."	Due to changing meteorological conditions imposed by climate change, the modeling of energy systems faces a transformation. As a result, a community of practice in energy–climate modelling, aiming to increase the integration of energy system models with weather and climate models, has developed [62]. Connecting energy aspects through coordinated action across technology, policy, and society to climate action is essential for effective climate change mitigation, a reduction in GHG emissions, and the achievement of climate goals. A shift toward renewable energy, increased efficiency, and inclusive, context-sensitive approaches requires coordinated action across sectors and disciplines to attain a sustainable, low-carbon future [63].
"Developing achievable business models and identifying funding opportunities: raising awareness and aspiring for political support regarding national programs; consideration of alternative renewable energy sources and technological solutions; exploring job creation and boosting local/regional economy."	A basic requirement for a PEB business model is the inclusion of a set-up of renewable energy and energy storage. The development of common business models and protocols to manage complexity and interdependencies is required and expected, but practice has shown that PEB business models are different according to geographical conditions, which impact both technology choices and energy needs. In addition, every country has its own building traditions, socioeconomic conditions, legislation, and building regulations. A practical roadmap, based on the business model, effectively guides the implementation and operation process [46].
"Investigating strategies suitable for existing urban structures: merging renewal and greening strategies; including stakeholders with a particular focus on landowners and citizens."	Aging infrastructure, heritage preservation, and dense populations are challenges that PEDs meet in existing urban structures. However, several retrofitting and integration strategies can facilitate existing districts to meet or exceed energy-positive targets [13]. Merging renewal and greening strategies in PEDs while meaningfully including stakeholders, particularly landowners and citizens, is both an opportunity and a challenge. Greening strategies concentrate on supporting well-being and livability by focusing on vegetation and green spaces, improved air quality, biodiversity, and urban cooling. Synergies between different approaches, such as circular economy, greening strategies, building renovation, and energy retrofits emphasize solutions such as PV-integrated shading, permeable surfaces, and green mobility. Circular economy is an evolving business model that is considered restorative. It is increasingly considered as an appropriate solution to achieving prosperity whilst acknowledging ecological and social boundaries.

The "Covenant of Mayors for Climate and Energy" is a voluntary movement of local authorities in the EU that develops and implements sustainable energy and climate policies that created a guidance framework for potential PED developers by focusing on leveraging the Sustainable Energy and Climate Action Plan (SECAP) methodology [64]. Additionally, common features between PED and SECAP processes were identified to effectively plan and monitor sustainable energy and climate action while also being aligned with specific KPIs. The framework underlines the importance of interoperability and synergies, concentrating on "shared principles, compatible frameworks, common data management, and specific integration points", and focuses on four main stages, that is, initiation, planning, implementation, and monitoring stages.

The project claims that the proposed framework supports PED replicability through its "comprehensive energy simulations, collaborative planning, and adaptive measures". PEDs are considered to be a significant solution toward sustainable urban areas, aiming to reduce GHG emissions and to enhance local resilience by integrating energy planning with broader urban development and stakeholder engagement. However, a good understanding and consideration of strategies, project features, and experiences form the basis for designing and developing a PED project. The SECAP highlights a strategic systemic approach that integrates climate, territorial, and energy planning. This entails analysis of the data regarding morphoclimatic zones (landforms associated with a particular climate), environmental variables and energy consumption, and the identification of targets and selection of site-specific actions, supported by robust indicators for progress monitoring, developing adaptation/mitigation actions, and increasing the environmental awareness of the involved actors. The four-stage methodology is not a new approach, and it was already defined as the project management lifecycle/project lifecycle in 1996 by the Project Management Body of Knowledge [65] and Prince2 [66] and is a continuously evolving process. The typical phases are initiation (project definition at a broad level), planning (establishing the scope, objectives, and procedures), implementation/execution (carrying out the project plan), monitoring/control (tracking progress and making necessary adjustments). In addition, a closure (finalizing and closing the project) follows. However, the SECAP introduces a new EU municipality integrating an urban planning paradigm related to energy efficiency and climate challenges. Citizen engagement, important in PED projects, is nevertheless a gray area [67] that needs a multi-faceted approach that requires particular caution, including application of combinations of factors, such as suitable incentives, adequate education/training, inclusive governance, effective communication, and active co-creation for boosting understanding, trust, and ownership regarding the measures adopted in the district of the citizen [47].

3.3. Third Study—The Annex 75 Project

The Annex 75 project of the "International Energy Agency" and "Energy in Building and Community", with 25 collaborating partner from 13 countries, investigated similarities and differences between them, emphasizing the balance between measures regarding energy efficiency and renewable energy [26]. According to the related outcomes, the technologies used in PEDs can be broadly categorized into (i) demand reduction/energy demand reduction technologies, (ii) energy distribution and supply systems energy, and (iii) storages. The readiness of the technologies should be assessed together with their cost efficiency. Similarly, the required stakeholder engagement, policy implications, and replicability should also be assessed, and prosumer models based on new energy community legislation should be considered.

The Annex 75 project developed a methodology for examining the renovation of buildings at the district level and its balance between cost-effective energy efficiency measures and renewable energy sources. Three KPI were identified as the most noteworthy in the methodology [26], namely,

1. Primary energy use (kWh/m^2 year);
2. Annualized total costs (EUR/m^2 year);
3. GHG emissions (CO_2 eq/m^2 year).

The sustainability and cost-effectiveness level of the renovation projects was defined with reference to these KPIs. Dynamic simulations (e.g., with an hourly time interval), were used for the evaluation of whole-system performance. The energy demands for heating and cooling are based on the building dimensions and thermal properties buildings. Electricity demand is calculated according to standard PED country profiles. Regarding the supply side, centralized and decentralized energy systems and specific interactions amongst the different technologies are considered in this methodology. The energy use for space heating and cooling, ventilation, lighting and building supplementary electricity consumption-integrated technical systems (pumps, fans, electric valves, pumps, etc.) was considered in the assessment. The characterization of energy systems involves four factors, namely "cost (as a function of capacity), service lifetime, conversion efficiency, and associated energy carrier". GHG emissions and consumption of primary energy are taken into consideration by using corresponding county emission factors and primary energy factors. This methodology was employed in a Portuguese real-life case study and the results were analyzed in detail. The study was considered significant for demonstrating the applicability of the methodology despite the fact that the results are from a certain Portuguese context.

Based on the Annex 75 framework, fifteen success stories were collected from seven European countries [26]. The success stories disclosed that renovation on a PED level is very complicated due to the high number of stakeholders involved, and the wide knowledge and considerable financial resources needed. A main challenge (bottleneck) identified was "the balance between energy efficiency measures and renewable energy use is based on expert estimations and not on calculations". District renovation was primarily initiated by the readiness and support of "the municipality, a housing association, a residents' association, or the wish of the inhabitants (tenants/residents)". Early-stage communication with tenants and citizens was significant for their engagement, which led to a significant overall satisfaction rate. Also, a suitable coordinator/facilitator is essential. Main drivers for PED utilization and its success were as follows:

- Raising the building to new modern standards regarding comfort and energy use: New modern standards for comfort and energy use in buildings focus on energy efficiency, indoor environmental quality, sustainability, and smart technology integration. These standards evolve regularly to reflect advances in climate science, design practices, materials, and occupant expectations. It should be noted that all new buildings in the EU should show zero-emission by 2030, and existing buildings by 2050.
- Improving open space attractiveness: PEDs should not only be sustainable but also livable, functional, live, energetic and vibrant in order to improve social acceptance and the accomplishment of sustainable initiatives, and encourage citizen and community participation in energy-saving behaviors. Open space attractiveness in PEDs is raised by (i) architectural esthetics design of urban areas, including green spaces, pedestrian-friendly streets, public spaces for interaction, events, community use, smart infrastructure and interaction, interactive energy displays and real-time feedback on consumption; (ii) microclimate control, such as shading, wind buffers, cooling via vegetation; (iii) noise reduction, adequate air quality, natural light; (iv) comfort and well-being; (v) integration of energy infrastructure, such as solar panels, into visual appearances; (vi) bike lanes and public transport access; (vii) accessibility (for all ages and abilities) and functionality; (viii) mixed-use zoning to safeguard vicinity to work, services, and leisure; (ix) social inclusiveness; (x) preservation of heritage and local identity; and (xi) spaces that evoke pride, belonging, and enjoyment.
- Developing the image of the district: Involving citizens from the very beginning in the PED project is identified as an effective measure for user acceptance and successful PEDs [46]. Improving open space attractiveness will also develop the image of the PED and increase economic value by attracting businesses and residents.

Funding is the main challenge regarding district renovation, but there also exist challenges such as coordination of stakeholders, creation of optimal renovation measures, and relocation of tenants during the renovation. Some of these challenges can be overcome with an appropriate business model, whilst other challenges, such as the legal framework, are more difficult to overcome.

Based on the related outcomes [26], the following implications can be highlighted:

- Combining energy efficiency upgrades in district renovations with renewable energy initiatives and wider urban or infrastructure improvements and social enhancement can create greater value and result in more efficient use of financial investments.
- Technologically, there are opportunities that would not be possible through individual solutions. However, there is a lack of technical know-how, knowledge, and protocols to simplify the complex process, as well as a lack of resources for coordination work depending on PED heterogeneity and complexity.
- The availability of financial resources is significant. The majority of PED projects are partially funded by European funding or other public funding.
- Good coordination and flexibility are required. Project phases should overlap to shorten long project timelines. The municipality has a critical role in integrated planning and municipal action.
- Public support is central for enabling stakeholder dialog, stakeholder commitment, and coordination work to successfully realize district renovation projects. The neighborhood association or similar social stakeholders in the district are proposed to be developed to aid this time- and resource-consuming process.

3.4. Fourth Study—Examination of Four PED Projects (Austria, Italy, the Netherlands, and Romania)

Bruckner et al. [57] reported their experiences and lessons learnt regarding four PEDs situated in Austria, Italy, Netherlands, and Romania, each of them with different climatic conditions and unique energy challenges, such as outdated infrastructure or heritage protection. They emphasized the significance of innovative technologies like photovoltaic-thermal systems, application of demand-side actions, and flexible grid usage. They emphasized that implementing PEDs in existing urban areas presents several challenges, including the absence of widely accepted methods for assessing energy balances, the complexity of integrating renewable energy systems into dense and concentrated urban infrastructures, and the need for multi-stakeholder awareness and collaboration to ensure smooth progress and foster local acceptance.

System boundaries were determined from several perspectives, namely, (i) Spatial: the geographical limits enclosing energy services and supplies; (ii) Temporal: the balancing period (one operational year); and (iii) Functional: Use of energy, functions, requirements (included or excluded), which can be grouped into the following:

- The innermost level—PED operational energy and user electricity;
- PED mobility aspects—everyday motorized private mobility;
- Climate-neutral PED—the outermost layer, PED-embodied energy and emissions associated with district construction, mobility, maintenance, and repair.

A simulation and assessment framework entitled "PEExcel", which is a decision support system, was developed for the "climate neutral Positive-Energy-District" in Austria [68]. The aims of the framework were to allow practitioners and researchers to speedily model and assess the PED primary energy and emission balance in an early planning phase.

4. PED Framework

The most significant success factors and lessons learnt from diverse existing international PED projects that can be applied to turn new PEDs into self-sustainable and greener urban neighborhoods are summarized in the PED Success Factor framework presented in Table 4. Specifically, the success factors and lessons learnt are categorized according to PED factors and presented following the order in which the different processes occur in the PED lifecycle. The framework is a process-oriented description of a PED that considers how such a district is planned, developed, and operated over its lifecycle. Process orientation entails by focusing on business processes rather than highlighting functional structure or hierarchy [69].

Table 4. PED Success Factor framework.

Stage	PED Factors	Success Factors
1. Initiation	Ideation Feasibility	Defining key objectives and high-level business case and rationale. What is the project trying to achieve? Defining broad scope and constraints. What are the initial risks, resources, and assumptions? Investigating funding potential, job creation and boosting of local/regional economy.
	Stakeholders	Identifying key stakeholders that will be affected and who should be involved.
	Technology	Identifying and creating an overview of diverse PED technology options by considering alternative renewable energy sources and technological solutions.
	Funding	Raising awareness and aspiring for political support regarding national programs.
	Policy	Securing political commitment.
	Aims	Identifying and aligning existing policies to complement PED aims and objectives
2. Planning	Business Goal	Developing achievable business models and identifying funding opportunities.
	Stakeholder Engagement	Motivating, encouraging, and engaging local stakeholders (community, citizens, residents, businesses, and civic organizations) and promoting collaboration among all stakeholders.
	Strategy	Developing a detailed strategy with the involvement of all relevant stakeholders.
	Measures	Defining specific, measurable, achievable, realistic, and timely (SMART) long-term goals and targets linked to community priorities.
	Action Plan	Transferring long-term goals into an action plan consisting of short-term objectives connected to specific milestones for greater clarity, direction, and focus.
3. Prototyping	Prototype	Potential implementation of a PED Lab for elaboration of guidelines and tools, experimentation and testing of different approaches and strategies, and monitoring of results (this step is not mandatory but provides insights before real-life application).
	Data	Ensuring early-stage interoperability through effective and robust data management frameworks and standardized protocols for successful interaction between energy generation, consumption, and storage systems at the district level.
4. Implementation	Monitoring	Implementing monitoring processes to track progress toward goals and objectives.
	Transparency	Ensuring progress transparency regarding the implementation of the action plan.
	Follow-up	Ensuring that the strategy is successfully implemented.
5. Evaluation	Assessment	Evaluating the effectiveness of the implemented actions.
6. Valorization	Dissemination Exploitation	Dissemination and exploitation of best practices for potential replication of identified PED success factors.

The success factors derive from the key aspects identified in the studies examined. The related studies focused on exploring multiple PEDs across different settings; hence, the related outcomes can be applied in various sectors. Figure 1 presents the key aspects identified within the studies examined. Specifically, Saheb et al. [45] displayed conclusions from a study of 62 projects regarding factors that are decisive for the proposed framework, namely success factors and challenges. The insights from 61 PED projects presented by Bossi et al. [24] focused on success factors and action areas, while the Annex 75 project with 25 collaborating partners by Terés-Zubiaga et al. [26] focused on lessons learnt and main drivers for the adoption, integration, and utilization of PEDs. Through the study of Bruckner et al. [57], which examined four PED projects, success factors and challenges were identified.

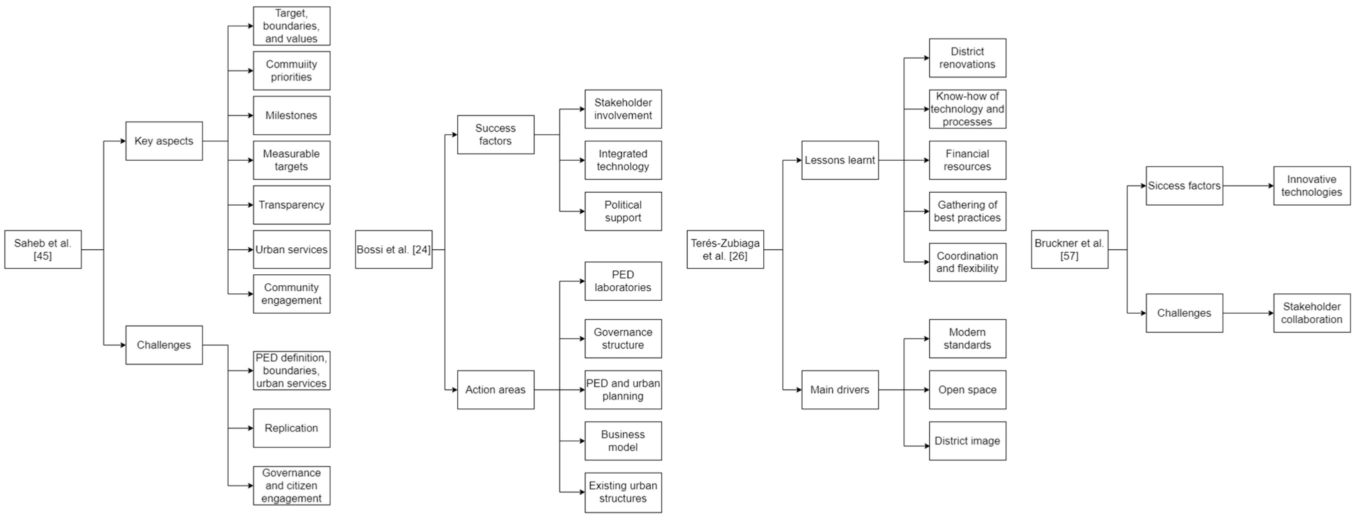

Figure 1. Key aspects identified from the related studies.

The PED framework can be used in business environments to make organizations more efficient and productive. It enables processes to be reviewed, optimized, and standardized and help in dealing with problems and challenges that might arise. The PMBOK [65] is a reference guide on how to complete a project in the best way. It is a set of processes, guidelines, best practices, and tools for managing projects. The principles of the PMBOK are used for the creation of the PED Success Factor framework.

Both PEDs and organizations are systems with interconnected components striving toward a common goal, but with different focuses. A PED aims to reach energy self-sufficiency and sustainability within an urban area, while an organization focuses on achieving specific business objectives. Both involve strategic planning, resource management, and stakeholder engagement to achieve their respective goals.

The overarching PED objective involves the creation of an urban district that produces more renewable energy than the energy it consumes over a year. The physical scope (neighborhood, business district, or mixed-use area) needs to be decided at an early stage through stakeholder engagement, such as city planners, residents, building owners, energy providers, and mobility operators. An important factor to take into consideration concerns whether the planned PED will be created in a new area or if building retrofits will be needed. New areas are easier to create, while in existing areas there may be challenges regarding aging infrastructure, heritage preservation, and ownership. In addition to the energy factor, PEDs also promise holistic sustainability, sharing of resources, and integrating environmental, economic, and social well-being. This entails addressing social challenges such as energy poverty and gentrification, and promoting inclusivity, citizen engagement, and improved well-being.

In the planning and design stage, the urban design integration and the energy demand need to be assessed together. Urban design integration includes high-efficiency buildings, mixed-use layouts, optimized spatial orientation, and mobility planning, while the energy demand concentrates on current and projected building energy use, mobility patterns, and infrastructure requirements. Energy balance scenarios are usually tested in a lab or with simulation to examine whether the positive energy goals set are feasible. Moreover, the consideration of contemporary, smart autonomous technology selection is required for optimizing the use of energy via smart applications, storage, and flexible consumption patterns.

In the operation stage, energy production and consumption across the district continuously need to be tracked to follow-up the collective self-consumption and peer-to-peer trading of energy, including mobility-energy integration of electric vehicles, change demand, and potential storage. Performance is evaluated by comparing actual performance to targets based on real data energy sharing rules and adjustable operations.

The PED Success Factor framework consists of success factors that are categorized in five stages according to the processes in the PED lifecycle, namely,

1. **Initiation:** This stage is the first phase in the PED project lifecycle. It is a high-level phase that plays a vital role in laying the foundation for the project's success. During this stage, the idea for the project is discussed, defined, evaluated, and authorized. Without an adequate initiation, the PED project may lack clear direction or stakeholder buy-in, increasing the risk of failure.
2. **Planning:** This stage is a critical phase where the project's roadmap is developed. It ensures clarity among stakeholders, provides direction for the implementation phase, and sets a baseline for tracking progress and for performance evaluation. It involves defining in detail the objectives, scope, timelines, resources, risks, and strategies necessary to complete the project successfully.
3. **Prototyping:** This stage in a project lifecycle is a phase where a preliminary version of the PED is developed to test key ideas or concepts, receive feedback, identify design and usability issues, and validate feasibility. The living labs in PEDs are prototypes that have been identified as particularly important for stakeholders and developers to understand how the final PED might be. As it involves stakeholders early, it reduces the risks of not meeting their needs. It also has the potential to detect design flaws or technical challenges before full-scale development begins.
4. **Implementation:** This stage in a project lifecycle is the phase where plans and strategies developed in earlier stages are put into action to create the actual deliverables of the project. It is the main phase of the PED project, transforming plans into tangible outcomes where resources, time, and effort are spent.
5. **Evaluation:** In this phase, the project is reviewed and assessed to determine how well it met its objectives, what did/did not work well, and what lessons can be learned for future projects. This stage is important because it aims to support accountability and transparency, improve future project planning and execution, and encourage continuous process improvement.
6. **Valorization**: Dissemination and exploitation of lessons learnt for making best practices and success factors available to other differing contexts.

Figure 2 provides an overview of the PED Success Factor framework in which the main stages of the PED lifecycle are shown in the sequence they occur. Below every stage, within the dotted box, the PED factors that need attention in that particular stage are highlighted. These factors have been identified to be pivotal for the successful creation and operation of PEDs.

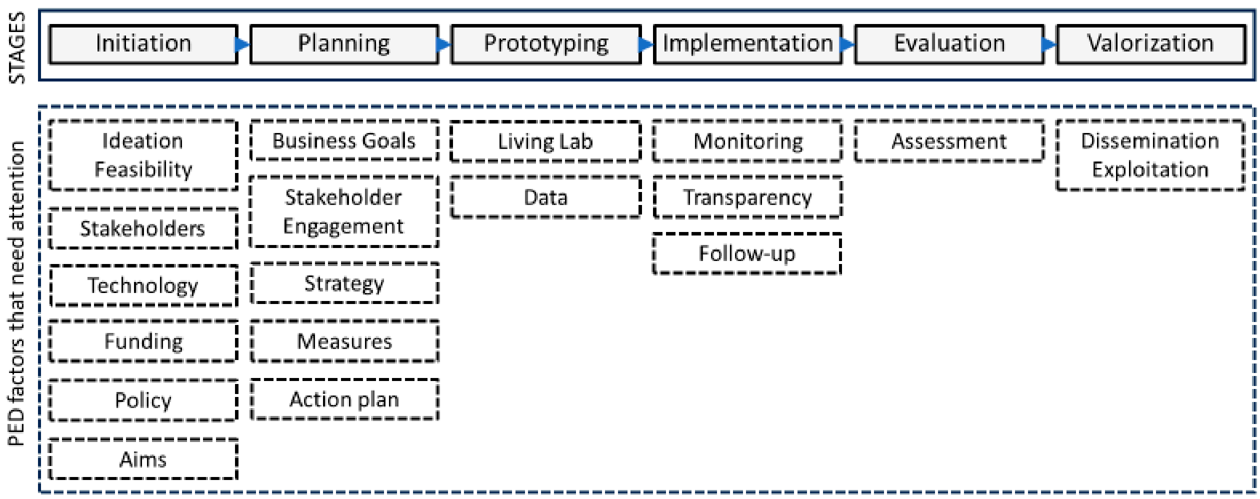

Figure 2. The PED Success Factor framework.

5. Discussion

In the strive for the EU to become climate-neutral by 2050 and a global role model regarding energy transition, open sharing of knowledge and sustainable energy solutions through collaboration and innovation is promoted. The aims of a PED ecosystem include the development and maintenance of attractive, self-sustainable, and economically viable EU urban areas, in which citizens, communities and their vicinity can thrive. The pioneering concept of PEDs is winning ground in the EU. The EU's SET-Plan, with its goal of establishing 100 PEDs in Europe by 2025, focuses on resource pooling, knowledge sharing, and collaborative solution development among stakeholders. The emphasis is on the planning, implementation, and replication of energy-efficient self-sustainable PEDs. Replication must be adapted to local needs and constraints. The main aim is to create a surplus of renewable energy in the 100 PEDs and to gradually expand the concept to wider areas. However, the results from the studies have shown that every PED context is different. Each district has unique climate, cultural, political, financial, and technical circumstances, making "one-size-fits-all" solutions unachievable. Recent studies have also highlighted the impact of autonomous and hydrogen-based hybrid energy systems, which can further facilitate the generation and distribution of energy even in rural areas and aid in achieving a sustainable future [70–72]. Additionally, it is evident that PEDs are interdependent [11] and have significant environmental impact [73], techno-economic implications [74], and a highly regarded role in achieving SDGs [75]. As a result, it is important to consider the social, environmental, and economic aspects of PEDs when assessing their development, adoption, and integration [76]. Focusing on approaches that encourage social innovation [61] and using suitable assessment methodologies [18] is vital for developing human-centric PEDs that emphasize well-being, inclusion, and justice [36].

Our proposed framework, which focuses on processes, is in line with the outcomes of other related studies which have also highlighted the significance of processes within PEDs. Processes orientation in PEDs refers to the structured, stepwise, and context-sensitive approaches needed to plan, implement, and scale PEDs effectively. Very few studies can be found in the literature that emphasize processes orientation in PEDs. Sareen et al. [77] for example, argued that a well-designed processes according to the various development phases is required in PEDs. The PED Success Factor framework brings forward the processes in all phases of the PED lifecycle. Other studies mention processes as a major component of PEDs. Turci et al. [78], for example, proposed the use of the Theory of Change (ToC) to facilitate PED implementation. The ToC is a structured process-oriented roadmap that outlines consecutive actions regarding how a PED project is expected to achieve its planned goals. Hence, processes have a central role in the ToC, which enables a shared understanding of a problem and supports decision making toward a solution. Similarly, Krangsås et al. [11] stated that the main challenges for developing PEDs are governance, incentive, social, process, market, technology, and context. To address the challenges, which are both interrelated and interdependent, the processes behind them need to be understood. Natanian et al. [79] also focused on a process-oriented perspective and emphasized that a holistic framework is needed to address the multi-dimensional challenges of the PED design process. Similarly, Kozlowska et al. [18] highlighted that to make coherent decisions in the PED design and planning process, social, ecological, and cultural factors need to be considered. Therefore, the proposed PED framework is process-oriented and focuses on key processes that lead to the successful adoption and implementation of PEDs.

The outcomes of this study contribute to widespread PED implementation through learning from challenges and success stories. The explanatory research approach used in this study enabled a deeper understanding of the PED phenomenon, clarification of diverse PED concepts, and the identification of patterns related to outcomes and lessons learned from existing PED projects. Reported success factors, good practices, policy guidelines, challenges, barriers, and obstacles were thoroughly investigated, evaluated, categorized, and compared to unveil patterns of lessons learnt from diverse existing international PED projects. The outcome of our study resulted in the PED Success Factor framework, which illustrates a description of the success factors that most frequently occur in the literature, organized according to the PED lifecycle processes.

Nevertheless, the two most frequently emphasized PED characteristics for success are stakeholder commitment and technological solutions. In particular, citizen commitment has already been recognized by the EU already through the creation of ECs. Stakeholder dynamics, which include the changing roles and perceptions of stakeholders, have been studied and found to be of utmost importance for successful PED implementation. In PEDs, stakeholders have shifting roles and diverse incentives among actors. Stakeholders need to be organized through interdisciplinary collaboration and supported by well-defined policies, stakeholder management frameworks, and effective governance to align interests and address multifaceted challenges. The main concerns for successful PED implementation are stakeholder co-operation (commitment and cross-disciplinary collaboration) and new measures for achieving high energy efficiency, local renewable energy generation, and energy storage and flexibility, as well as energy sufficiency.

A PED ecosystem depends on a wide range of technological solutions, including smart meters, smart technologies, intelligent software agents, Internet of Things, peer-to-peer networks, and blockchain-based systems for secure and transparent transactions. Standardized protocols and robust data management frameworks are needed to integrate the different technologies and maximize interoperability, which is a critical aspect for microgrid operation and interconnected distributed solar home systems, known as mesh grids or swarm electrification. Data exchange platforms enable interoperability within the ecosystems, enabling seamless interaction and integration among various energy systems, technologies, and stakeholders. Security and integration standards are evolving. The clean energy market, which utilizes renewable energy sources with minimal impact on the environment, is increasingly dependent on digital technologies and interconnected infrastructures, which in turn creates increased potential cyber threats and cybersecurity concerns regarding how to secure reliable operations of interconnected PED systems.

6. Conclusions

A main incentive for piloting a number of PED cases in the EU until 2025 has been the creation of a foundation for understanding the benefits, values, scalability, and replicability. The results from diverse projects have shown that a holistic cross-disciplinary approach for mainstreaming PEDs or their fundamental components across a larger number of settings is crucial, requiring the integration of STEEPLED aspects for effective planning and design.

PEDs are fundamental for achieving sustainable urban development through their enhancement of energy self-sufficiency and reduction in GHG emissions. They have steadily gained significance and recognition on the policy agenda of the European Commission regarding energy transition. PEDs aim at achieving a net positive energy balance and reduced GHG emissions through high energy efficiency, renewable energy generation, and energy flexibility at the district level, as well as extensive stakeholder involvement and collaboration. PEDs face challenges associated with governance, context-specific factors and integration of STEEPLED factors.

The emphasis of this study was to gather insight into the factors used by the EU municipalities that have been the frontrunner in setting up PEDs. It was noticed that buildings that are substantially energy-efficient are at the cornerstone of low-carbon communities. The aim of this study was to examine existing PED initiatives by looking at PED eco-systems and documented success factors to unveil what lessons learnt from various existing international projects could be applied to turn new PEDs into greener and self-sustainable urban neighborhoods. The main contribution of this study is the proposed PED Success Factor framework, which is a process-oriented framework that presents key processes that are required for the successful creation, adoption, and operation of PEDs based on the experiences and outcomes of PEDs.

Future work will concentrate on analyzing the influences of STEEPLED factors on PEDs. Specifically, emphasis will be placed on the role of each STEEPLED factor in the context of PEDs and how they may be interrelated to each other. This will help us extend the PED Success Factor framework processes with a more detailed description of each process, including technology integrations, time and cost, tasks, roles, and risk factors, such as cybersecurity threats, data privacy and safety, digital literacy, and energy poverty. Additionally, given the exploratory nature of this study, the proposed framework not yet being validated through a case study and the study not adopting a systematic approach can be regarded as the main limitations. Hence, future studies are encouraged to further examine the key aspects of PEDs through a systematic literature approach to identify key enabling technologies and issues that need to be addressed. Moreover, there is a need for case studies to be conducted to explore the implications and impact of PEDs and the role of stakeholders in their successful realization. It is also important to avoid gentrification when greening districts and ensuring equal access to the required resources and infrastructure. Hence, it is vital to identify the key mechanisms that ensure that low-income and underprivileged residents as well as vulnerable groups are not excluded from the merits that PEDs can bring. However, given their social influence, it is important to further examine the social KPIs of PEDs, such as energy affordability and resident satisfaction. As PEDs are highly reliant on technology, future studies should put emphasis on identifying key cybersecurity threats in interconnected grids, on ethical concerns, and on data security and privacy issues.

Author Contributions: Conceptualization, D.S. and K.S.; methodology, D.S. and K.S.; formal analysis, D.S., K.S. and G.L.; investigation, D.S. and K.S.; data curation, D.S. and K.S.; writing—original draft preparation, D.S., K.S. and G.L.; writing—review and editing, D.S., K.S. and G.L.; visualization, D.S.; supervision, K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partly carried out as part of the "Positive Energy Districts in Kanta-Häme (EKA+)" project by Häme University of Applied Sciences HAMK and Sykli Oy. The project was partly funded by the European Union and the Regional Council of Kanta-Häme.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All of the data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. United Nations. *United Nations Generating Power.* Available online: https://www.un.org/en/climatechange/climate-solutions/cities-pollution (accessed on 30 March 2025).
2. European Commission. 2050 Long-Term Strategy—European Commission. Available online: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en (accessed on 15 May 2025).
3. European Commission. Directive—EU-2024/1275—EN—EUR-Lex. Available online: https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng (accessed on 5 March 2025).
4. European Commission. Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy from Renewable Sources, and Repealing Council Directive (EU) 2015/652. Available online: https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng (accessed on 20 May 2025).
5. European Commission. Directive (EU) 2019/944 of the European Parliament and of the Counceil of 5 June 2019—On Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU. Available online: https://eur-lex.europa.eu/eli/dir/2019/944/oj/eng (accessed on 20 May 2025).
6. European Commission. Effort Sharing Regulation (ESR) | EESC. 2021. Available online: https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/effort-sharing-regulation-esr (accessed on 25 April 2025).
7. European Commission. Energy Efficiency Directive. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en (accessed on 25 April 2025).
8. European Commission. EU Emissions Trading System (EU ETS)—European Commission. Available online: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (accessed on 25 April 2025).
9. Lv, Y. Transitioning to sustainable energy: Opportunities, challenges, and the potential of blockchain technology. *Front. Energy Res.* **2023**, *11*, 1258044. [CrossRef]
10. United Nations. The 17 Goals. Available online: https://sdgs.un.org/goals (accessed on 3 March 2025).
11. Krangsås, S.G.; Steemers, K.; Konstantinou, T.; Soutullo, S.; Liu, M.; Giancola, E.; Prebreza, B.; Ashrafian, T.; Murauskaitė, L.; Maas, N. Positive Energy Districts: Identifying Challenges and Interdependencies. *Sustainability* **2021**, *13*, 10551. [CrossRef]
12. Wu, Y. Decentralized transactive energy community in edge grid with positive buildings and interactive electric vehicles. *Int. J. Electr. Power Energy Syst.* **2022**, *135*, 107510. [CrossRef]
13. Soutullo, S.; Giancola, E.; Sánchez, M.N.; Ferrer, J.A.; García, D.; Súarez, M.J.; Prieto, J.I.; Antuña-Yudego, E.; Carús, J.L.; Fernández, M.Á.; et al. Methodology for Quantifying the Energy Saving Potentials Combining Building Retrofitting, Solar Thermal Energy and Geothermal Resources. *Energies* **2020**, *2020*, 5970. [CrossRef]
14. Monti, A.; Pesch, D.; Ellis, K.A.; Mancarella, P. Chapter One—Introduction. In *Energy Positive Neighborhoods and Smart Energy Districts*; Monti, A., Pesch, D., Ellis, K.A., Mancarella, P., Eds.; Academic Press: Cambridge, MA, USA, 2017; pp. 1–5. [CrossRef]
15. European Commission. SET Plan Progress Report 2024. Available online: https://setis.ec.europa.eu/set-plan-progress-report-2024_en (accessed on 26 April 2025).
16. Positive Energy Districts—European Commission. Available online: https://setis.ec.europa.eu/working-groups/positive-energy-districts_en (accessed on 15 May 2025).
17. JPI Urban Europe. Positive Energy Districts (PED). Available online: https://jpi-urbaneurope.eu/ped/ (accessed on 15 May 2025).
18. Kozlowska, A.; Guarino, F.; Volpe, R.; Bisello, A.; Gabaldòn, A.; Rezaei, A.; Albert-Seifried, V.; Alpagut, B.; Vandevyvere, H.; Reda, F.; et al. Positive Energy Districts: Fundamentals, Assessment Methodologies, Modeling and Research Gaps. *Energies* **2024**, *17*, 4425. [CrossRef]
19. Gollner, C.; Hinterberger, R.; Noll, M.; Meyer, S.; Schwarz, H.-G. Booklet of Positive Energy District in Europe. Urban Europe. 2019. Available online: https://jpi-urbaneurope.eu/wp-content/uploads/2019/04/Booklet-of-PEDs_JPI-UE_v5_NO-ADD.pdf (accessed on 20 May 2025).

20. European Commission. Clean Energy for all Europeans Package Completed: Good for Consumers, Good for Growth and Jobs, and Good for the Planet—European Commission. Available online: https://commission.europa.eu/news/clean-energy-all-europeans-package-completed-good-consumers-good-growth-and-jobs-and-good-planet-2019-05-22_en (accessed on 26 April 2025).
21. European Commision. Energy Poverty. 2025. Available online: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-poverty_en (accessed on 30 March 2025).
22. Hearn, A.X. Positive energy district stakeholder perceptions and measures for energy vulnerability mitigation. *Appl. Energy* **2022**, *322*, 119477. [CrossRef]
23. European Commision. REPowerEU 2022. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en (accessed on 26 April 2025).
24. Bossi, S.; Gollner, C.; Theierling, S. Toward 100 Positive Energy Districts in Europe: Preliminary Data Analysis of 61 European Cases. *Energies* **2020**, *13*, 6083. [CrossRef]
25. European Commision. In Focus: Energy Efficiency in Buildings—European Commission. 2020. Available online: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en (accessed on 2 May 2025).
26. Terés-Zubiaga, J. Cost-effective building renovation at district level combining energy efficiency & renewables—Methodology assessment proposed in IEA EBC Annex 75 and a demonstration case study. *Energy Build.* **2020**, *224*, 110280. [CrossRef]
27. Shnapp, S.; Paci, D.; Bertoldi, P. *Enabling Positive Energy Districts Across Europe: Energy Efficiency Couples Renewable Energy*; Publication Office of the European Union: Luxembourg, 2020. [CrossRef]
28. Habib, M.K.; Chimsom, I.C. CPS: Role, Characteristics, Architectures and Future Potentials. *Procedia Comput. Sci.* **2022**, *200*, 1347–1358. [CrossRef]
29. Cicceri, G.; Tricomi, G.; D'Agati, L.; Longo, F.; Merlino, G.; Puliafito, A. A Deep Learning-Driven Self-Conscious Distributed Cyber-Physical System for Renewable Energy Communities. *Sensors* **2023**, *23*, 4549. [CrossRef]
30. Siakas, D.; Lampropoulos, G.; Siakas, K. Autonomous Cyber-Physical Systems Enabling Smart Positive Energy Districts. *Appl. Sci.* **2025**, *15*, 7502. [CrossRef]
31. Vinuesa, R.; Azizpour, H.; Leite, I.; Balaam, M.; Dignum, V.; Domisch, S.; Fuso Nerini, F. The Role of Artificial Intelligence in Achieving the Sustainable Development Goals. *Nat. Commun.* **2020**, *11*, 233. [CrossRef]
32. Clerici Maestosi, P. Harmonizing Urban Innovation: Exploring the Nexus between Smart Cities and Positive Energy Districts. *Energies* **2024**, *17*, 3422. [CrossRef]
33. Zhang, X.; Shen, J.; Saini, P.K.; Lovati, M.; Han, M.; Huang, P.; Huang, Z. Digital Twin for Accelerating Sustainability in Positive Energy District: A Review of Simulation Tools and Applications. *Front. Sustain. Cities* **2021**, *3*, 663269. [CrossRef]
34. Borah, S.S.; Khanal, A.; Sundaravadivel, P. Emerging Technologies for Automation in Environmental Sensing: Review. *Appl. Sci.* **2024**, *14*, 3531. [CrossRef]
35. Agostinelli, S.; Cumo, F.; Guidi, G.; Tomazzoli, C. Cyber-Physical Systems Improving Building Energy Management: Digital Twin and Artificial Intelligence. *Energies* **2021**, *14*, 2338. [CrossRef]
36. Nguyen, M.T.; Batel, S. A Critical Framework to Develop Human-Centric Positive Energy Districts: Toward Justice, Inclusion, and Well-Being. Front. *Sustain. Cities* **2021**, *3*, 691236. [CrossRef]
37. Lee, K.; Man, K.L. Edge Computing for Internet of Things. *Electronics* **2022**, *11*, 1239. [CrossRef]
38. Wang, Y.; Chen, C.-F.; Kong, P.-Y.; Li, H.; Wen, Q. A Cyber–Physical–Social Perspective on Future Smart Distribution Systems. *Proc. IEEE* **2023**, *111*, 694–724. [CrossRef]
39. Delicato, F.C.; Al-Anbuky, A.; Wang, K.I.-K. Editorial: Smart Cyber–Physical Systems: Toward Pervasive Intelligence systems. *Future Gener. Comput. Syst.* **2020**, *107*, 1134–1139. [CrossRef]
40. Zhang, J.J.; Wang, F.-Y.; Wang, X.; Xiong, G.; Zhu, F.; Lv, Y.; Hou, J.; Han, S.; Yuan, Y.; Lu, Q.; et al. Cyber-Physical-Social Systems: The State of the Art and Perspectives. *IEEE Trans. Comput. Soc. Syst.* **2018**, *5*, 829–840. [CrossRef]
41. Skinner, E.; Dancis, J.; Descriptive and Explanatory Designs. Human Development. 2020. Available online: https://pdx.pressbooks.pub/humandevelopment/chapter/descriptive-and-explanatory-designs/ (accessed on 20 May 2025).
42. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
43. Jesson, J.; Lacey, F. How to do (or not to do) a critical literature review. *Pharm. Educ.* **2006**, *6*, 139–148. [CrossRef]
44. Rouse, P.; Sherkat, O.; O'Grady, W. Dynamic Stakeholder Analysis Through Process Mapping. *Financ. Account. Manag.* **2025**, *41*, 398–418. [CrossRef]
45. Saheb, Y.; Shnapp, S.; Johnson, C. The Zero Energy concept: Making the whole greater than the sum of the parts to meet the Paris Climate Agreement's objectives. *Curr. Opin. Environ. Sustain.* **2018**, *30*, 138–150. [CrossRef]
46. Siakas, D.; Rahanu, H.; Georgiadou, E.; Siakas, K.; Lampropoulos, G. Positive Energy Districts Enabling Smart Energy Communities. *Energies* **2025**, *18*, 3131. [CrossRef]
47. Fatima, Z.; Pollmer, U.; Santala, S.-S.; Kontu, K.; Ticklen, M. Citizens and Positive Energy Districts: Are Espoo and Leipzig Ready for PEDs? *Buildings* **2021**, *11*, 102. [CrossRef]

48. Mamidi, A.P. Strategic Project Management: Bridging the Gap Between Strategy and Execution. Master's Thesis, University of Vaasa, Vaasa, Finland, 2025.
49. Cai, S.; Gou, Z. Transitioning Positive Energy Buildings toward Positive Energy Communities: Leveraging Performance Indicators for Site Planning Assessments. *Energy Build.* **2024**, *325*, 114976. [CrossRef]
50. Barrutieta, X.; Kolbasnikova, A.; Irulegi, O.; Hernández, R. Decision-making framework for positive energy building design through key performance indicators relating geometry, localization, energy and PV system integration. *Energy Build.* **2023**, *297*, 113442. [CrossRef]
51. Chatzikonstantinidis, K.; Giama, E.; Fokaides, P.A.; Papadopoulos, A.M. Smart Readiness Indicator (SRI) as a Decision-Making Tool for Low Carbon Buildings. *Energies* **2024**, *17*, 1406. [CrossRef]
52. Lampropoulos, G.; Garzón, J.; Misra, S.; Siakas, K. The Role of Artificial Intelligence of Things in Achieving Sustainable Development Goals: State of the Art. *Sensors* **2024**, *24*, 1091. [CrossRef]
53. Cortinovis, C.; Geneletti, D. A performance-based planning approach integrating supply and demand of urban ecosystem services. *Landsc. Urban Plan.* **2020**, *201*, 103842. [CrossRef]
54. JPI Urban Europe/SET Plan Action 3.2. White Paper on PED Reference Framework for Positive Energy Districts and Neighbourhoods. 2020. Available online: https://jpi-urbaneurope.eu/wp-content/uploads/2021/10/setplan_smartcities_implementationplan-2.pdf (accessed on 20 May 2025).
55. Derkenbaeva, E.; Vega, S.H.; Hofstede, G.J.; Van Leeuwen, E. Positive Energy Districts: Mainstreaming Energy Transition in Urban Areas. *Renew. Sustain. Energy Rev.* **2022**, *153*, 111782. [CrossRef]
56. Boccalatte, A.; Fossa, M.; Gaillard, L.; Ménézo, C. Microclimate and Urban Morphology Effects on Building Energy Demand in Different European Cities. *Energy Build.* **2020**, *224*, 110129. [CrossRef]
57. Bruckner, H.; Alyokhina, S.; Schneider, S.; Binder, M.; Abdin, Z.U.; Santbergen, R.; Verkou, M.; Zeman, M.; Isabella, O.; Pagliarini, M.; et al. Lessons Learned from Four Real-Life Case Studies: Energy Balance Calculations for Implementing Positive Energy Districts. *Energies* **2025**, *18*, 560. [CrossRef]
58. Nguyen, M.T.; Batel, S. Which energy citizenship in positive energy districts? A governmentality social psychological analysis of participatory governance. *J. Environ. Policy Plan.* **2024**, *26*, 117–130. [CrossRef]
59. Silvast, A.; Valkenburg, G. Energy citizenship: A critical perspective. *Energy Res. Soc. Sci.* **2023**, *98*, 102995. [CrossRef]
60. Ryghaug, M.; Skjølsvold, T.M.; Heidenreich, S. Creating energy citizenship through material participation. *Soc. Stud. Sci.* **2018**, *48*, 283–303. [CrossRef]
61. Baer, D.; Loewen, B.; Cheng, C.; Thomsen, J.; Wyckmans, A.; Temeljotov-Salaj, A.; Ahlers, D. Approaches to Social Innovation in Positive Energy Districts (PEDs)—A Comparison of Norwegian Projects. *Sustainability* **2021**, *13*, 7362. [CrossRef]
62. Craig, M.T.; Wohland, J.; Stoop, L.P.; Kies, A.; Pickering, B.; Bloomfield, H.C.; Browell, J.; De Felice, M.; Dent, C.J.; Deroubaix, A.; et al. Overcoming the disconnect between energy system and climate modeling. *Joule* **2022**, *6*, 1405–1417. [CrossRef]
63. Kılkış, Ş.; Krajačić, G.; Duić, N.; Rosen, M.; Al-Nimr, M. Effective mitigation of climate change with sustainable development of energy, water and environment systems. *Energy Convers. Manag.* **2022**, *269*, 116146. [CrossRef]
64. Davide, M.; Bastos, J.; Bezerra, P.; Hernandez, M.G.; Palermo, V.; Pittalis, M.; Todeschi, V.; Treville, A.; Barbosa, P.; Melica, G. *How to Develop a Sustainable Energy and Climate Action Plan (SECAP)—Covenant of Mayors Guidebook—Main Document*; Publications Office of the European Union: Luxembourg, 2025. [CrossRef]
65. PMI. PMBOK Guide | Project Management Institute. Available online: https://www.pmi.org/standards/pmbok (accessed on 1 July 2025).
66. Axelos. PRINCE2 Certification | Qualifications and Exams | Axelos. Available online: https://www.axelos.com/certifications/propath/prince2-project-management (accessed on 1 July 2025).
67. Scorza, F.; Santopietro, L. A systemic perspective for the Sustainable Energy and Climate Action Plan (SECAP). *Eur. Plan. Stud.* **2024**, *32*, 281–301. [CrossRef]
68. Schneider, S.; Drexel, R.; Zelger, T.; Baptista, J. PEExcel: A Fast One-Stop-Shop Assessment and Simulation Framework for Positive Energy Districts. In Proceedings of the BauSim Conference 2024, IBPSA-Germany and Austria, Vienna, Austria, 10–12 September 2024; Volume 10, pp. 80–88. [CrossRef]
69. Kohlbacher, M.; Gruenwald, S. Process orientation: Conceptualization and measurement. *Bus. Process Manag. J.* **2011**, *17*, 267–283. [CrossRef]
70. Khan, S.A.; Tao, Z.; Agyekum, E.B.; Fahad, S.; Tahir, M.; Salman, M. Sustainable rural electrification: Energy-economic feasibility analysis of autonomous hydrogen-based hybrid energy system. *Int. J. Hydrog. Energy* **2025**, *141*, 460–473. [CrossRef]
71. Rosen, M.A.; Koohi-Fayegh, S. The Prospects for Hydrogen as an Energy Carrier: An Overview of Hydrogen Energy and Hydrogen Energy Systems. *Energy Ecol. Environ.* **2016**, *1*, 10–29. [CrossRef]
72. Yue, M.; Lambert, H.; Pahon, E.; Roche, R.; Jemei, S.; Hissel, D. Hydrogen Energy Systems: A Critical Review of Technologies, Applications, Trends and Challenges. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111180. [CrossRef]

73. Volpe, R.; Bisello, A.; Tuerk, A.; Guarino, F.; Giancola, E.; Sanchez, M.N.; Reda, F. Linking Environmental Impact Assessment and Positive Energy Districts: A Literature Review. *Clean. Environ. Syst.* **2025**, *16*, 100264. [CrossRef]
74. Wang, G.; Gilmont, O.; Blondeau, J. Pathways to Positive Energy Districts: A Comprehensive Techno-Economic and Environmental Analysis Using Multi-Objective Optimization. *Energies* **2025**, *18*, 1134. [CrossRef]
75. Cellura, M.; Fichera, A.; Guarino, F.; Volpe, R. Leveraging Positive Energy Districts Surplus for the Achievement of the Sustainable Development Goals. *Energies* **2025**, *18*, 506. [CrossRef]
76. Casamassima, L.; Bottecchia, L.; Bruck, A.; Kranzl, L.; Haas, R. Economic, social, and environmental aspects of Positive Energy Districts—A review. *Wiley Interdiscip. Rev. Energy Environ.* **2022**, *11*, e452. [CrossRef]
77. Sareen, S.; Albert-Seifried, V.; Aelenei, L.; Reda, F.; Etminan, G.; Andreucci, M.-B.; Kuzmic, M.; Maas, N.; Seco, O.; Civiero, P.; et al. Ten questions concerning positive energy districts. *Build. Environ.* **2022**, *216*, 109017. [CrossRef]
78. Turci, G.; Civiero, P.; Aparisi-Cerdá, I.; Marotta, I.; Massa, G. Transition Approaches towards Positive Energy Districts: A Systematic Review. *Buildings* **2024**, *14*, 3039. [CrossRef]
79. Natanian, J.; Guarino, F.; Manapragada, N.; Magyari, A.; Naboni, E.; De Luca, F.; Cellura, S.; Brunetti, A.; Reith, A. Ten questions on tools and methods for positive energy districts. *Build. Environ.* **2024**, *255*, 111429. [CrossRef]