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Positive energy districts: Mainstreaming energy transition in urban areas

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A R T I C L E I N F O

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A B S T R A C T

The concept of Positive Energy Districts (PEDs) has emerged to facilitate the energy transition and contribute to climate neutrality through energy efficiency and net zero energy balance. There are several similar concepts with a common goal that a building, neighborhood, or district can meet its energy demands from low-cost, locally available, environmentally friendly renewable sources. However, there is a lack of comprehensiveness and consistency among these existing concepts that could lead to misinterpretations. Therefore, the main aim of this study is to develop a comprehensive view on the PED concept with a focus on urban residential areas in Europe, with insights also being useful for other areas. The analysis is based on a literature review of PEDs and similar concepts, as well as a review of PED practical examples. The literature review compares PEDs based on geographical scale, identifying defining elements and metrics that provide insights on how to define and operationalize PEDs. The study reveals that real-life PEDs tend to go beyond the frames set by the definitions because the concept fails to consider the contextual factors that are inherent in them. To develop a comprehensive concept of PEDs, a Complex Adaptive System approach is taken, also incorporating the Doughnut view, which represents the system holistically. This view is also important in designing a resilient system, as energy systems are often exposed to disruptions. Additionally, the study discusses the PED concept's limitations and key issues, such as electric mobility, that merit more attention.

1. Introduction

Energy transition has become a priority to achieve the Sustainable Development Goals, particularly, (7) Affordable and Clean Energy, (11) Sustainable Cities and Communities, and (13) Climate Action. This commitment has been reflected in various programs such as *Energiewende* [1], the 2015 United Nations Sustainable Development Goals, and in the global climate action agenda under the 2016 Paris Agreement and United Nations Framework Convention on Climate Change (UNFCCC) [2]. A challenge connected with energy transition is energy poverty: inaccessibility and prohibitive cost of renewable energy services [3,4]. Evidently, climate change and energy poverty are urgent concerns and require transitioning to more sustainable yet reliable energy systems.

The energy system transformation incorporates socio-economic, technological, environmental, political and institutional challenges that need to be tackled simultaneously. As part of a holistic urban strategy, the innovative concept of Positive Energy Districts (PEDs) emerged to facilitate the transformation. PEDs are embedded in urban and regional energy systems dominantly driven by renewable energy aiming to provide security and flexibility of energy supply [5]. As such, PEDs have become an integral part of sustainable urbanization strategies. The European Union (EU) has introduced the Strategic Energy Technology Plan with a target to establish 100 PEDs by 2025 [6] in order to contribute to climate neutrality through energy efficiency and net zero energy balance.

PEDs arose from earlier concepts with comparable meanings [7]. Extensively discussed concepts and terms include *(Net) Zero Energy Buildings* [7–11], *Nearly Zero Energy Buildings* [12], *Energy Positive Neighborhoods* [13–16], *Positive Energy Blocks* [17,18], *Energy Neutral Districts* [19], and *Positive Energy Districts* [5,6,20]. A key common thread among these concepts is the goal that a building, neighborhood, or district is able to meet its energy demands from low-cost, locally available, environmentally friendly renewable sources. However, there is still no commonly agreed definition of PEDs. The definitions remain generic,

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Abbreviations:

CAS	Complex Adaptive System
CO_2	Carbon dioxide
END	Energy Neutral District
EPN	Energy Positive Neighborhood
EV	Electric Vehicle
IPCC	Intergovernmental Panel for Climate Change
KPI	Key Performance Indicator
LC-ZEB	Life Cycle Zero Energy Building
PEB	Positive Energy Block
PED	Positive Energy District
UNFCCC	United Nations Framework Convention on Climate Change
ZEB	Zero Energy Building

and their variety allows for different interpretations. Since PEDs are the most recently used concept by the EU to indicate local-level energy transition, it is meaningful to develop a consistent conceptual framework of PEDs that represents the common essence of existing concepts and that is more inclusive by bringing in key elements that are currently largely lacking.

This study significantly contributes to the literature by developing a comprehensive view on the PED concept and integrating the Complex Adaptive Systems (CAS) and Doughnut Economics views into PEDs. These two frameworks enrich the PED concept by comprising the complexity and resilience of PEDs to boost the local energy transition. The aims are to synthesize concepts related to PEDs, review practical examples of PEDs, and develop a comprehensive view on PEDs. Synthesizing the concepts will grant an overview of existing PED and similar definitions, allowing to identify key knowledge gaps. Then, zooming in on practical examples of already implemented PEDs in Europe will enable a better understanding of how the conceptual and practical advancements differ, as well as which elements prevail in practice that are missing in the concepts. Finally, based on these overviews, a more comprehensive view on PEDs is developed incorporating insights from CAS and Doughnut Economics views [21,22]. PEDs as CAS are seen through the lens of Doughnut Economics that recognizes the systemic nature of the economy with an emphasis on climate neutrality and energy poverty.

The remainder of the article is organized as follows. Section 2 introduces the approach taken for the development of the comprehensive view on the PED concept. Section 3 presents an overview of the existing concepts related to PEDs and discusses assessment metrics for analyzing energy performance. Section 4 illustrates practical examples of PEDs implemented in Europe at different scales. Based on both the conceptual and practical advancements of PEDs, Section 5 develops a comprehensive view on PEDs, and discusses limitations and key issues that merit more attention. Section 6 finalizes this study with concluding remarks.

2. Materials and methods

The focus of this study is on urban residential areas due to their importance in the energy transition process. The analysis is based on a comprehensive literature review of PEDs and similar concepts, and a critical review of PED practical examples. The literature review of the conceptual foundation of PEDs is carried out based on geographical scale, identifying defining elements and assessment metrics. This fills a gap in the literature, as previous studies have not compared the elements and metrics of PED-related concepts based on geographical scale.

The review of the practical examples provides a representation of possible scales for implementation and variations of different solutions for real-life PEDs. These examples are selected from several PEDs that have already been implemented in Europe. In this study, a list of selected PEDs and information on them is based on the *Booklet of PEDs* [23] and *Value Generation by PEDs: Best Practices Case Study Book* [24]. Additional information is collected from the official websites of the selected PED projects [25–30]. The examples' selection was guided by a set of criteria [24]: (1) needs to contribute to energy generation, distribution, and management; (2) has to be implemented and operational; (3) aims to address social aspects; (4) has a focus on Europe. These criteria are derived from the reference framework for PEDs based on the EU Strategic Energy Technology Plan [5] that suggests the definition of PEDs.

The PED examples satisfy these criteria. However, Derkenbaeva et al. (2020) use the term "PED-like" areas highlighting that despite satisfying the abovementioned criteria, some of the examples are not fully PEDs or are projects that contributed to PED implementation. Both the *Booklet of PEDs* [23] and *Value Generation by PEDs: Best Practices Case Study Book* [24] present a large number of examples including PED areas and other related projects. Because the scope of this study is residential areas, only PEDs implemented in residential areas have been selected from the two mentioned lists, which are in total 11 examples. These 11 PED examples are discussed further.

Together, the review of PED-related concepts and practical examples serve to provide a more comprehensive view on PEDs (Fig. 1). This is in turn useful for identifying how PEDs differ in their concept and practice, what lenses PEDs should be seen through, discovering knowledge gaps, and formulating an ideal vision for conceptualizing and implementing PEDs.

3. The state of the art on PEDs

This section presents an overview of the differences in defining elements and assessment metrics. PED-related literature has been developing for more than a decade, receiving increasing attention due to the severity of energy and environmental crises. At the core of the PED concept is the ambition to overcome these crises. PEDs are viewed as a pivotal means of contributing to a transition away from fossil fuel dependence toward the use of more renewable energy and achieving climate neutrality.

3.1. Defining PEDs

While earlier studies have mostly focused on individual buildings, recent studies extend the boundaries to neighborhood and district scales. The existing concepts include the following defining elements that are consistent across the *(Net/Nearly) Zero Energy Buildings* (ZEB)/*Energy Positive Neighborhoods* (EPN)/*Positive Energy Blocks* (PEB)/*Energy Neutral Districts* (END)/*Positive Energy Districts* (PED): (1) a geographical boundary; (2) a state of interaction with an energy grid; (3) an energy supply method; and (4) a balancing period (see Table 1). The overview is based on the central distinct element – geographical boundary, while the other elements vary within the geographical boundary. It is important to

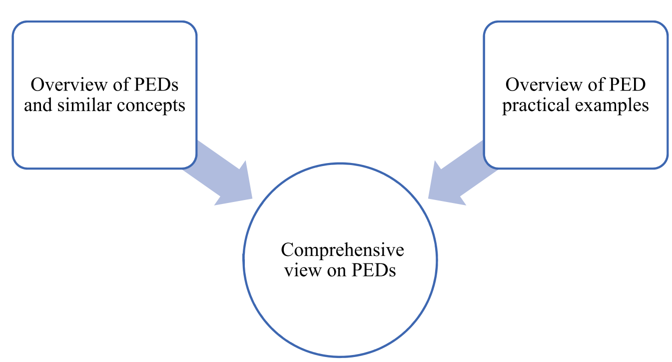

Fig. 1. Steps in developing a comprehensive view on PEDs.

Table 1
Overview of the definitions from the literature.

Concept	Definition	Defining elements				Literature sources
		Geographical boundary	State of interaction with an energy grid	Energy supply method	Balancing period	
Zero Energy Building (ZEB)	(1) **Net Zero Site Energy Building that produces as much energy as it uses annually when accounted for at the site**, (2) Net Zero Source Energy Building that produces at least as much energy as it uses annually, when accounted for at the source, (3) Net Zero Energy Emissions Building that produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources, and (4) Net Zero Energy Cost Building that receives as much financial credit for exported energy as it is charged on the utility bills.	Building	Off-grid	On-site	Annual	Torcellini et al. (2006)
Zero Energy Building/ Net Zero Energy Building (ZEB/Net ZEB)	ZEB is an energy-efficient building able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand (refers to **autonomous** buildings). Net ZEB indicates the **connection to the smart grid**, which enables two-way interaction.		Off-grid/On-grid	On-site/ off-site	Annual	Sartori et al. (2012); Marszal et al. (2011); Kolokotsa et al. (2011)
Life cycle Zero Energy Building (LC-ZEB)	LC-ZEB is a building where the primary energy used in the building and the energy embodied within its materials and systems **over the lifetime** of the building is equal or less than the energy produced by its renewable energy systems within the building over the lifetime of the building.		Off-grid	On-site	Annual life cycle	Hernandez and Kenny (2010)
Energy Positive Neighborhood (EPN)	Energy Positive Neighborhood is an area that **generates more** electricity **than it consumes.**	Neighborhood	Off-grid	On-site	Annual	Ala-Juusela et al. (2016); Monti et al. (2016)
Positive Energy Block (PEB)	Positive Energy Block is a set of at least three buildings in close proximity that have an average yearly **positive energy balance** between them.		On-grid	On-site/ Off-site	Annual	Ahlers et al. (2019); Backe et al. (2019)
Energy Neutral District (END)	Energy Neutral District is a district where, on a yearly basis, **no net energy import** is required from outside the district (refers to self-sufficiency).	District	On-grid	On-site/ Off-site	Annual	Jablonska et al. (2012)
Positive Energy District (PED)	*Positive Energy District* is an energy-efficient and energy-flexible urban area or a group of connected buildings, which produces **net zero** greenhouse gas emissions and actively manages an annual **local or regional** surplus production of renewable energy.		On-grid	On-site/ Off-site	Annual	TWG of the European Strategic Energy Technology (2018); JPI Urban Europe/SET Plan Action 3.2 (2020), Lindholm et al. (2021)

define a clear geographical boundary because specified areas (a building, a neighborhood, or a district) are treated as a single unit with demand, local supply, and storage [15] addressing the scale of energy-efficient area.

3.1.1. Building scale

Definitions of the ZEB/EPN/PEB/END/PED may vary depending on local contexts and goals of stakeholders – policymakers, investors, energy users. Therefore, Torcellini et al. (2006) propose four different definitions of *Zero Energy Building* (ZEB): (1) *Net Zero Site Energy Building* that produces as much energy as it uses annually when accounted for at the site, (2) *Net Zero Source Energy Building* that produces at least as much energy as it uses annually when accounted for at the source,[1] (3) *Net Zero Energy Emissions Building* that produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources, and (4) *Net Zero Energy Cost Building* that receives as much financial credit for exported energy as it is charged on the utility bills. Among these four definitions, the site ZEB is the most consistent definition because it can be verified through on-site measurements and has the fewest external fluctuations that influence the ZEB goal. In contrast, the source, emissions, and cost ZEBs are not consistent and cannot be measured directly because site-to-source factors need to be determined and there are unpredictable fluctuations in energy costs [8].

Sartori et al. (2012) refer to a ZEB as “an energy-efficient building able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand.” However, the authors point out that this definition is more general and includes autonomous buildings that do not interact with the energy grids (including electrical grids and heat networks), while the term Net ZEB indicates the connection to the grid (smart grid), which enables two-way interaction. Similarly, Marszal et al. (2011) also discuss the differences between a ZEB and Net ZEB through the lenses of the terms “off-grid[2]”

[1] Refers to the primary energy used to generate and deliver the energy to the site [8].

[2] ZEB is not connected to any utility grid and hence needs to use some electricity storage system for periods with peak loads and also known as ‘autonomous’ or ‘self-sufficient’ [7].

and "on-grid[3]" ZEB. The "on-grid" ZEB or a Net ZEB is favored due to the vitality of two-way interaction in order to avoid the issue of large storage capacity, backup generators, energy losses while storing and over-producing the energy [7]. In line with this, the authors highlight a number of requirements that should be considered before Net ZEBs are constructed to comply with the term "on-grid" ZEB. The prerequisites include energy efficiency, indoor climate, and building-grid interaction. Kolokotsa et al. (2011) also highlight that the presence of the "two-way" is essential, with the aim of resulting in a net-positive or zero export of power from the building to the electrical grid. "Two-way" flow in combination with minimization of the energy consumption and energy generation based on renewable energy sources (such as solar power, wind power, hydro power, geothermal energy, biomass) leads to a Net ZEB [10].

While the Net ZEB definition introduced by Sartori et al. (2012), Marszal et al. (2011), and Kolokotsa et al. (2011) has parallels with the definition of the source ZEB introduced by Torcellini et al. (2006), Hernandez and Kenny (2010) introduce *Life Cycle Zero Energy Building* (LC-ZEB) that includes the embodied energy of the building and its components in addition to the annual energy use. LC-ZEB is defined as a building where the primary energy used in the building and the energy embodied within its materials and systems over the lifetime of the building is equal or less than the energy produced by its renewable energy systems within the building over the lifetime of the building [9].

3.1.2. Neighborhood scale

In line with changes in energy systems, the recent literature suggests broadened definitions of a ZEB extended to the neighborhood and district scales. This refutes the notion that a single building is the most effective unit to result in higher energy gains. In this context, district is considered as a larger area that is comprised of neighborhoods. Ala-Juusela et al. (2016) use a similar definition of the concept as in previous studies [7,10,11] applying it to a neighborhood scale. The energy demand of a neighborhood includes the energy demand of buildings and other infrastructures, such as waste and water management, parks, open spaces, and public lighting, as well as the energy demand for transport.

Monti et al. (2016) define *Energy Positive Neighborhood* (EPN) as an area that generates more electricity than it consumes. The authors address the key defining features of the future energy systems that include increasing penetration of low carbon electricity production, electric heating, and transport. Given the nature of renewable energy sources (non-schedulable as well as partly non-dispatchable), flexibility is a desired goal that is prioritized at EPNs over being energy positive [14].

Ahlers et al. (2019) propose scaling up from buildings to blocks, and further to a wider scale of neighborhoods and districts with the aim to create climate-friendly and livable urban environments. The authors define a *Positive Energy Block* (PEB) as a set of at least three buildings in proximity that have an average yearly positive energy balance between them [17]. The same definition is provided by Backe et al. (2019). This definition allows to focus on the infrastructure and systems between buildings as part of the built environment. The buildings serve different purposes to optimize local renewable energy production, consumption, and storage. Interaction between PEBs and their neighboring blocks can lead to a *Positive Energy District* (PED), where PEBs become smaller components of the PED [17,18].

3.1.3. District scale

So far, district-level systems have not received adequate attention. While only a few authors focused on wider areas such as districts in their studies of energy transition [17–20], the PED concept has gained more attention in policy-oriented works [5,6].

Jablonska et al. (2012) characterize an *Energy Neutral District* (END) as a district where, on a yearly basis, no net energy import is required from outside the district. ENDs require interaction between a larger group of buildings than in a neighborhood, users and the regional energy, mobility and ICT system in a holistic approach [18]. The interaction of ENDs with their surrounding districts through exporting in case of energy surplus and importing in case of shortage proves ENDs to be efficient [19]. ENDs are considered an integral part of the district energy system and embedded in the spatial, economic, technical, environmental, and social context [17].

PEDs have a similar meaning as ENDs, while energy positivity is an ill-defined term and has an ambiguous connotation [14]. The term "Positive Energy District" is composed of, "Positive Energy" and "District". First, "Positive Energy" refers to an energy surplus where the (renewable) energy production exceeds the consumption over a certain timeframe [6]. More recently, the extended definition incorporates the environmental aspect, in which "Positive Energy" implies net zero CO_2 emissions through energy generation based on entirely renewable sources [5]. Second, "District" refers to a larger area of the city, which is larger than a block or a neighborhood, as an extension of earlier concepts of PEBs and EPNs.

Lindholm et al. (2021) distinguish three types of PEDs: autonomous, dynamic, and virtual. The difference between these types is their ability to interact with energy networks, consumers, and producers outside their geographical boundaries. While autonomous PED is a district with the energy demand covered by internally generated renewable energy where energy imports are not allowed, dynamic and virtual PEDs are flexible in their interaction beyond the geographical boundaries [20]. The authors highlight that dynamic PEDs imply interaction within the local area, with neighboring areas, and with the energy grid that allows a lot of flexibility in the system, whereas virtual PEDs rely on renewable energy systems and energy storage outside their geographical boundaries. Renewable energy generation systems installed outside the geographical boundaries of PEDs are called virtual power plants[4] (VPPs). VPPs benefit virtual PEDs by enabling them to utilize a larger variety of renewable energy sources and lower costs of energy storage that can extensively contribute to energy flexibility.

The goal of EPNs and PEDs is not merely to achieve energy *positivity* [13], but to achieve energy balance – the amount of energy produced is equal to the amount consumed [6]. The reference framework for PEDs (based on national consultation within the EU) outlines three important functions of urban areas in the context of energy systems: *energy production* completely based on renewable energy, *energy efficiency* for best utilization of renewable energy produced, and *energy flexibility* for optimality in the urban energy system [5]. These three functions are defining milestones of PEDs, which are bound to the guiding principles to achieve climate neutrality, social inclusiveness and energy justice, resilience and security of energy supply [5]. The framework suggests energy efficiency to be the priority, as the space needed for the generation of renewable energy is always limited in an urban area.

3.2. Operationalizing PEDs

Assessment metrics play a significant role in implementing, comparing, and replicating PEDs. Thus, the metrics are expected to reflect the defining elements of the PED concept.

3.2.1. Energy performance within a geographical boundary

A geographical boundary is one of the defining elements of PEDs.

[3] ZEB has the connection to one or more energy infrastructures, therefore, it has the possibility of both purchasing energy from the grid and feeding in excess energy to the grid to avoid on-site storage and also known as 'net-zero energy' or 'grid integrated' (Ibid).

[4] A network of decentralized, medium-scale power generating units such as wind farms, solar parks, and Combined Heat and Power (CHP) units, as well as flexible power consumers and storage systems [20].

However, it can only be characterized qualitatively by a unit (a building, a neighborhood, or a district) that gives an idea of the area size. The areas are treated as a single unit while assessing the scale of energy-efficient areas. Therefore, it is fundamental to specify these units while addressing the metrics.

The other defining elements of the PEDs and overall, the energy performance is assessed within a geographical boundary. Ala-Juusela et al. (2016) and Monti et al. (2016) propose a general set of indicators to assess energy efficiency. More specifically, these indicators relate to energy (energy consumption, generation, efficiency label), economic (energy cost, energy sold to the grid, energy cost savings), and environmental (CO_2 emissions, energy savings) aspects [13,14]. While these indicators provide a broad scope of energy efficiency, indicators related to contextual and individual factors are still required to contribute to a clearer indication of the PEDs' energy performance.

3.2.2. Interaction with an energy grid

To optimize energy use, two-way communication between buildings and energy grids (smart grids) has become an important element. Different indicators and approaches have been proposed to analyze the building-to-grid interaction [7]. From a building perspective, Sartori et al. (2012) introduce a *grid interaction index*. The grid interaction index represents the variability of the energy flow within a year, where the energy flow is a net export that is defined as a difference between exported and delivered energy within a given time interval [11]. From the viewpoint of a grid, the authors highlight an important characteristic: *grid interaction flexibility*, which allows response to signals from the smart grid such as price signals, and therefore, adjusts load, generation, and storage control [11]. For this purpose, it is meaningful to assess grid interaction flexibility hourly or even with a higher time resolution. Assessing grid interaction flexibility with such a high time resolution is a focus of import/export energy balance calculation and contributes to providing more complete information on the interaction with the smart grid [11]. In contrast, with monthly values that are sufficient to calculate load/generation balance, grid interaction is often overlooked due to focusing only on calculating the loads.

Additionally, Sartori et al. (2012) introduce the weighting system with the aim to convert the physical units of different energy carriers into uniform metrics in order to create common balance metrics. Similarly to the categories of ZEB defined in Torcellini et al. (2006), the authors introduce four types of metrics: site energy, source energy, energy cost, and carbon emissions related to energy use [11]. Within these metrics, they distinguish between symmetric[5] weighting and asymmetric[6] weighting. Different weighting factors can be assigned to different technologies generating the same carrier.

3.2.3. Energy supply method

As one of the defining elements, energy supply gained significant attention in the literature on PEDs and similar concepts [7,8]. Torcellini et al. (2006) are one of the first who extensively contributed to the concept of on-site and off-site energy supply. While the on-site supply is distinguished between supply within the building footprint (located on the building) and the building site (located on-site but not on the building), the off-site supply indicates that the building either uses renewable energy sources available off-site to produce energy on-site or purchases off-site renewable energy sources [7]. However, as noted by Marszal et al. (2011), there is ambiguity in renewable energy supply that in some cases is seen as on-site when focusing on the actual location of the energy generation, while in other cases as off-site when focusing on the fuel's origin. Therefore, clear distinctions and definitions of energy supply methods need to be outlined for a common understanding of PEDs.

3.2.4. Balancing period

A balancing period has been heavily discussed in the literature on PEDs and similar concepts, where the annual energy balance is the most accepted one for calculating the energy balance [7,13]. To measure the annual balance between local energy supply and demand, Ala-Juusela et al. (2016) designed a set of Key Performance Indicators (KPIs). The foremost KPI, "On-site Energy Ratio (OER)" measures the balance between energy demand and supply from the local renewable energy sources. However, because the OER is generic as it does not consider the time of energy demand and supply (e.g. peak energy demand time) and different types of energy, the authors include additional KPIs.[7] Another option is the sub-yearly balance such as seasonal or monthly [7]. These balancing periods allow energy supply systems to better match the actual energy demand. Nevertheless, it is more challenging to achieve zero balance than in the case of annual balance because of the seasonal differences between energy demand and renewable energy generation [7].

Another alternative for the annual energy balance is a life cycle balance, also known as service life of a building [9,16]. Hernandez and Kenny (2010) argue that the full life cycle of the building (e.g. 50 years[8]) is a more appropriate period to assess the energy balance. Calculations of the life cycle of the building incorporate not only the operating energy use, but also the energy embodied in the building materials, construction, and technical installations and, thus, assess the environmental impact of the building[9] [9]. Similarly, Walker et al. (2018) propose a combined approach of Life Cycle Performance Design and KPIs (LCPD based KPIs) to evaluate the level of sustainability and include the lifetime performance of both buildings and energy infrastructure.

Among the approaches for calculating the annual energy balance, Sartori et al. (2012) suggest using static accounting in order to avoid the complexity of calculations and assumption of time-dependent patterns. However, static accounting does not consider uncertain parameters such as unpredictable use behavior, changing weather conditions, and other time-varying parameters that affect energy efficiency. To limit this uncertainty, dynamic accounting is considered a more suitable approach to measure energy performance as it enables measuring in real-time using smart metering that also allows obtaining energy users' preferences communicated on a daily or hourly basis [10].

[5] The rationale behind symmetric weighting is that the energy exported to grids can avoid an equivalent generation somewhere else in the grid. It is applied to cases when the energy generated on-site does not affect the balance negatively (in terms of costs or emissions), which means the value of the exported energy is equal to the average weighting factor for the grid [11].

[6] The rationale behind the asymmetric approach is that energy demand and supply do not have the same value, which means that delivered and exported energy should be weighted differently in accordance with this principle. It is applied to account for the negative effect of on-site energy generation if that is not accounted for somewhere else in the grid (Ibid).

[7] *Annual Mismatch Ratio (AMR)* measures the amount of energy imported into the neighborhood in the case of each energy type, per year.*Maximum Hourly Surplus (MHSx)* measures what is the maximum value on how much bigger the hourly local renewable supply for each energy type is than the demand during that hour, per year.*Maximum Hourly Deficit (MHDx)* measures the maximum value of how much bigger the hourly local demand is compared to the local renewable supply during that hour, per year.*Monthly Ratio of Peak hourly demand to Lowest hourly demand (RPLx)* measures how big is the peak power demand [13].

[8] Suggested as a typical value for the service life of buildings when no other data is available [9].

[9] These calculations are expressed through *Annual Energy Use (AEU)*, *Annualized Embodied Energy (AEE)*, and *Annualized Life Cycle Energy (ALCE),* which is a sum of AEU and AEE and gives a life cycle perspective of energy use, where AEU, AEE, and ALCE are expressed in primary energy units per year of service life. At a life cycle ZEB, the ALCE tends to zero, reflecting a true value of efforts to minimize energy use in the built environment (Ibid).

4. PED practical examples

With a thorough conceptual perspective on PED and similar concepts, zooming in on real-life PEDs can provide additional insights. This section thus presents representative examples of 11 PEDs[10] that have already been implemented in Europe.

4.1. Defining elements of the PED practical examples

The selected PEDs are analyzed following the key defining elements identified in the previous section (Table 2). The 11 PEDs are not completely based on renewable energy [24]. While some are more self-sufficient than others, they are still dependent on an additional supply of energy in the low renewable energy supply periods. Thus, they do not fully satisfy the definition and are not entirely PEDs but have the goal to follow the path toward it.

While the examples vary in their scales, they are not limited to a district. In fact, PEDs can go beyond the district boundaries and still deliver relatively similar results, especially in the case of islands. Like other energy systems, islands aim at utilizing renewable energy to supply their energy demands. However, by their nature, islands are under higher pressure due to their isolation from the mainland and higher dependence on their natural surroundings [31]. In the case of islands, more efforts are required to achieve the results than in urban areas. Evidently, the PED and similar concepts can be applied to wider scales.

All selected PED examples showcase the interaction with a smart grid. In some cases, the PEDs are largely self-sufficient and involve limited interaction with the energy grid (examples 1, 2, 4, 5, 7, 9), while in other cases, the PEDs generate less own energy and are more dependent on the grid (examples 3, 6, 8, 10, 11). Consequently, the energy supply method in all examples is also characterized as on-site with partial off-site. This means that some of the energy is generated on-site, while some is generated off-site and is imported to meet the energy demand, which shows that none of the 11 PED examples is autonomous, but rather are dynamic PEDs. Moreover, for a significant share of the building stock, especially in densely populated urban areas, plus-energy standard or Net ZEB standard is not practical for the near future with current technologies, system boundaries, and economic incentives [32]. Hence, the existing PEDs do not provide “proof-of-concept”.

Table 2
Overview of the PED examples in Europe.

Nº	PED example	Defining elements		
		Geographical boundary	State of interaction with an energy grid	Energy supply method
1	Schoonschip, the Netherlands	Neighborhood	On-grid (smart), one connection to the energy network	On-site (+passive off-site)
2	Aardehuizen, the Netherlands		On-grid (largely self-sufficient)	On-site (+passive off-site)
3	Hunziker Areal, Switzerland	District	On-grid	On-site/Off-site
4	District of Vauban, Germany		On-grid (largely self-sufficient)	On-site (+passive off-site)
5	La Fleuriaye West (Carquefou), France		On-grid (largely self-sufficient)	On-site (+passive off-site)
6	IssyGrid/Fort d’Issy, France		On-grid (smart)	On-site/off-site
7	Samsø Island, Denmark	Island	On-grid (largely self-sufficient)	On-site (+passive off-site)
8	The Orkney Islands, the UK		On-grid	On-site/off-site
9	Isle of Eigg, the UK		On-grid (largely self-sufficient)	On-site (+passive off-site)
10	The Åland Islands, Finland		On-grid	On-site/off-site
11	Goeree-Overflakkee Island, the Netherlands		On-grid	On-site/off-site

Note: The information on the selected PED examples’ balancing period is not available. There is also a lack of information on how the energy performance of these PEDs is assessed.

4.2. Extended overview of the PED practical examples

As can be observed, the examples based on the key defining elements fall short of providing a complete picture of the PEDs. Thus, to gain a better understanding of the PEDs in practice, a more comprehensive overview is needed.

PEDs are designed as an integral part of the district energy system and subject to be intrinsically scalable up to districts and cities and are embedded in the spatial, economic, technological, environmental, and social context [17]. This means PEDs depend on their contextual factors, and therefore, differ based on them (Table 3) [23–31]. Fig. 2 offers a visualization of the different geographic scales and contextual factors of real-life PEDs in residential areas.

With the priority of energy transition to tackle challenges such as climate change and energy poverty, PEDs mainly pursue environmental and social goals. Environmental goals are focused on combating climate change and decreasing dependence on fossil fuels by reducing CO_2 emissions, using sustainable mobility, and becoming self-sufficient based on RE. These targets are central and consistent across all examples. Another prevailing effort of PEDs is to reduce energy poverty. This social goal includes reducing energy bills, making energy available and affordable for all groups of end-users, and creating a livable and safe environment. Together, environmental and social goals require actions from different groups of stakeholders, their initiative, and collaboration. Clearly, the 11 PEDs demonstrate the importance of these ingredients that have contributed to an acceleration of the energy transition, showcasing initiative and strong engagement of citizens as well as collaboration with other stakeholders making PEDs possible [24].

Despite their similar goals, the contextual factors are different and demand distinct approaches in achieving the PED goals [24,33]. One of the contextual factors that play a role in PED implementation is spatial. Spatial features may include geographic characteristics such as a physical scale of an area (e.g., neighborhood, district, city, region) or non-geographic – area type (e.g., residential, industrial, business district), and building type (newly built/existing). Among the 11 examples, there are residential areas with newly constructed buildings (examples 1–5) including those built on wastelands (example 3) and in old industrial districts (example 1) and residential areas with already existing buildings (examples 6–10). Additionally, geographic characteristics include climate conditions that are characterized by temperature, precipitation, and wind [4], but also include, inter alia, latitude, elevation, topography, distance from/to the ocean, location on a continent. Altogether, these spatial features play a role in designing different pathways toward implementing PEDs.

[10] 11 PEDs from Gollner et al. (2019) and Derkenbaeva et al. (2020) fit the scope of this study. Other examples from the list are not considered PEDs because they are not fully PEDs (pilot projects, technology test platforms, PEDs in implementation and planning stage); or projects of private companies that are contributing to PEDs implementation by e.g., providing renewable energy and data-driven technologies (solar panels, smart meters, batteries, etc.).

Table 3
Extended overview of the PED examples.

Nº	PED example	Geographical boundary	Contextual factors				
			Spatial	Technological	Economic	Environmental	Social
1	Schoonschip, the Netherlands	Neighborhood	Newly built 46 homes (100 residents)	Solar panels, heat pumps, storage batteries	Own investments	Self-sufficient based on RE, climate neutral	Initiated by the citizens, cooperation with the municipality and other partners
2	Aardehuizen, the Netherlands		Newly built 23 homes	Solar panels, thermal mass, heat pumps	Own investments	Ecological area with self-sufficient earth houses	Initiated by the citizens, cooperation with the municipality and regional experts
3	Hunziker Areal, Switzerland	District	Newly built 13 buildings (1300 residents)	District heating based on warm exhaust air, rooftop solar panels, and smart energy optimization platforms	Saving up to 30% of annual heating costs; revenue from the energy sales	Reduce energy consumption, CO_2 emissions	Collaboration of residents (cooperative members), the municipality, architects, neighbors
4	District of Vauban, Germany		Newly built 2000 homes (5100 residents)	Solar panels, district heating, passive housing	Reduced energy costs, revenue from the energy sales	Self-sufficient based on RE, reduced emissions, sustainable mobility	Initiated by the citizens, supported by the city
5	La Fleuriaye West (Carquefou), France		Newly built district, 600 homes (320 delivered, 300 by 2022)	Solar panels, biomass, passive housing	Shared investments by partners, reduced energy costs	Self-sufficient based on RE	Initiated by the city, collaboration with 18 partners
6	IssyGrid/Fort d'Issy, France		1600 homes	Solar panels, smart grid, meters, storage batteries	Shared investments by partnering companies, revenue from energy sales	Reduced emissions	Initiated by private property developer, collaboration with other private partners
7	Samsø Island, Denmark	Island	3724 residents	Wind turbines, solar panels, biomass	70% of the investments came from local investors and residents, revenue from the energy sales, annual financial returns from investments, subsidies of up to 30% for renewable energy technologies installations and energy efficiency refurbishments	Self-sufficient based on RE, recycling of waste, sustainable mobility	Initiated by the citizens, cooperation with the municipality, local energy agency, the local development office and the municipally owned energy company
8	The Orkney Islands, the UK		22 000 residents	Wind turbines	Revenue from energy sales	Self-sufficient based on RE	Initiated by the local community
9	Isle of Eigg, the UK		96 residents	Hydroelectric plants, wind turbines, solar panels, storage batteries	EU funding, islanders' investment, a bank loan, reduced energy costs	Self-sufficiency based on renewable energy sources	Initiated by the citizens
10	The Åland Islands, Finland		3000 residents	Solar panels, wind turbines, wave and geothermal energy, storage batteries	Public – private – people partnership	Self-sufficiency based on renewable energy sources	Collaboration of citizens, the municipality, private stakeholders, research organizations
11	Goeree-Overflakkee Island, the Netherlands		Half of the island (22 000 households)	Wind turbines, solar panels	Local investments, receiving a yearly revenue of 6% from the dividends	Self-sufficiency based on renewable energy	Initiated by the citizens

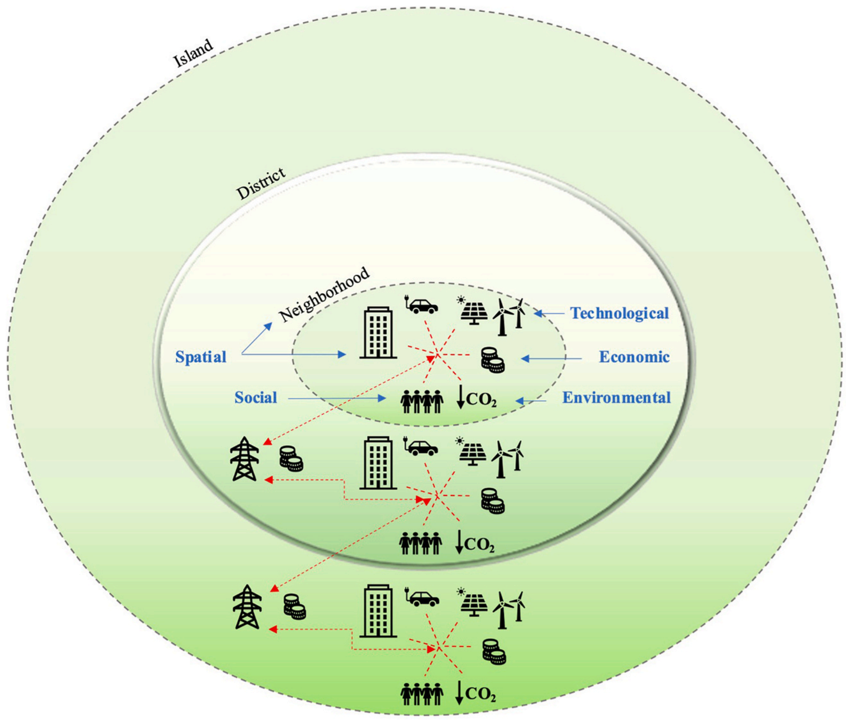

Fig. 2. Real-life PEDs in residential areas.

These spatial features are an important aspect for applying suitable technological solutions. For example, PEDs that have larger scales and are in the northern part of the region (examples 7–11) generate their energy using wind, while PEDs at a smaller scale and located closer to the south (examples 1–6) tend to generate their energy using solar and heat energy. Also, technological solutions depend on existing energy infrastructure. Energy infrastructure encompasses numerous components such as generation, transmission, and distribution of energy, physical networks of pipelines, and other transportation elements [34]. Depending on these infrastructural characteristics, suitable technologies or a combination of technologies can be installed. As seen in all 11 PEDs, a combination of technologies is more effective for the energy system based on renewable energy due to its fluctuating nature and allows PEDs to achieve efficiency and flexibility [24].

To implement technological solutions including technology purchase and installation, adequate funding is required as PEDs are more expensive than traditional projects. The main source of financing usually comes from the partnership of several stakeholders including local citizens, municipalities, and private companies. While in most of the examples the investments in technological solutions were made with the environmental and social goals, two PEDs (examples 6 and 8), seen as opportunity-driven, invested primarily pursuing an economic goal – to create revenue from energy sales. Nevertheless, all PEDs have gained different economic benefits such as dividends from their investments, reduced energy costs and savings, and revenue from energy sales to the grid.

Another contextual factor is environmental. Environmental factors include pollutants and temperature, where pollutants cause air/environment contamination and temperature rises to various extents. This creates different environmental contexts in different localities. Therefore, the environmental factors also determine what techno-economic solutions should be implemented.

Finally, social factors were fundamental for the stakeholders in the 11 PEDs to take actions such as vis-à-vis initiating the PEDs and collaborating to implement them. These factors vary significantly as they include culturally related features, inter alia, identity, trust, power relations, sense of community. While some PEDs (examples 1–4 and 7–11) are initiated bottom-up, others (examples 5 and 6) are initiated top-down.

5. Comprehensive view on PEDs

The proliferation of studies with diverse definitions of PEDs together with the growing number of PEDs in practice calls for the development of a practicable yet comprehensive view on the concept.

5.1. PEDs as resilient complex adaptive systems

5.1.1. Complex adaptive systems framework

Complex adaptive systems (CAS) is a powerful framework for studying dynamics and resilience [35]. As the name suggests, a CAS is a complex system that consists of dynamic network of interactions of its components, and it is adaptive as it adjusts to the changing environment. The CAS components are able to organize autonomously following a set of rules. Their complex (micro) behaviors create non-linear dynamics due to new or changing interactions, based on which macro nature of the system emerges [35]. Additionally, the macro nature of the system is profoundly dependent on the past decisions and behaviors that have led the evolution of the system in particular directions. Importantly, the complexity of the system is also characterized by interaction of sub-systems (e.g. technologies, institutions, business models, etc.) that mutually coevolve and complement each other.

Evidently, the main properties of CAS include components, networks, dynamics, self-organization, path dependency, emergence, coevolution, learning and adaptation [21]. All these characteristics formulate the paradigm of CAS. Central to CAS is that any element of the system cannot be understood separately, but must be defined holistically as a system of components and their interactions. The multidisciplinary nature of this phenomenon allows applying CAS to a wide variety of research domains.

5.1.2. PEDs as complex adaptive energy systems

The energy transition requires substantial energy efficiency measures, urgent adoption of innovative technologies, policies and

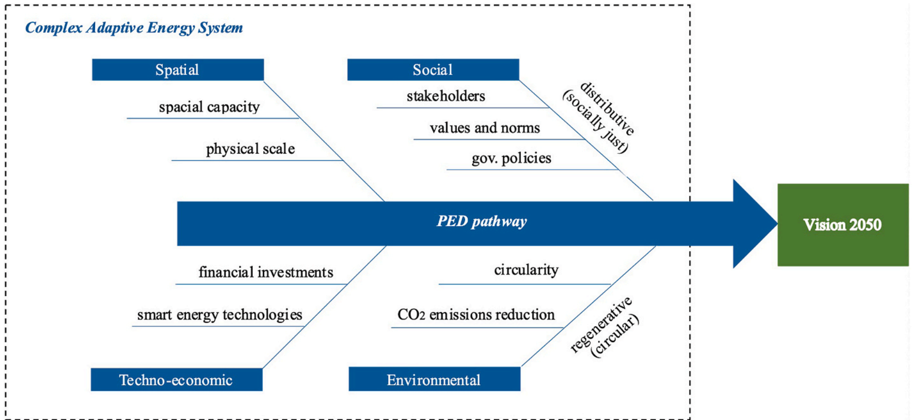

Fig. 3. Doughnut pathway toward the vision.

regulations, and financial investments that are rather uncertain. This process is driven by heterogeneous agents of energy systems such as end-users, companies, regulators, and governments, sometimes with conflicting interests. These agents and technologies interact through physical and social networks governed by institutional structures creating the environment wherein the energy systems operate [21]. Their interaction changes over time according to dynamic rules, which emerge with the availability of new technologies, policies, and decision-making processes. Together, these elements make energy systems examples of complex systems. This is well demonstrated by the practical examples of PEDs that incorporate these elements. However, the existing PED and similar concepts are less comprehensive and do not mirror this complexity.

Complex systems are adaptive insofar as they have the capacity to change under the influence of social, physical, and other factors of the environment (e.g., political, economic). Thus, energy systems are CAS incorporating heterogeneous elements (agents and technologies) that interact and create impacts on other parts of the system [21]. Hence, if one wishes to understand their function, these components must be considered within the system. The practical advancement of PEDs demonstrates the complexity of energy systems by the interrelations of the spatial, techno-economic, social, and environmental aspects, which can be referred to as sub-systems. All these aspects forming a comprehensive overview of PEDs are essential to develop pathways toward the Vision 2050 (Fig. 3). The Vision comprises the aim of the EU to be climate-neutral by 2050 that is at the heart of the European Green Deal, and is in line with the EU's commitment to global climate action under the Paris Agreement [36].

As the most densely populated, urban areas experience space constraints. Finding a suitable location for energy infrastructure installations has become a serious challenge. By their nature, renewable energy-related technologies (such as solar panels, wind turbines, heat pumps, energy storage batteries, etc.) demand ample space to be installed. Identifying building or district spatial capacity will be key for solving a technical part of the energy transition. Another point to consider is climate conditions, which matters for finding suitable renewable energy technologies that can be utilized at full capacity.

Considering the complexity of energy systems, a combination of different technological solutions will be essential, which highly depends on the spatial features of the area. The implementation of technological solutions, such as installation of smart energy technologies and refurbishment of a built environment, requires extensive investments [37]. With these, efficient and economically feasible technological solutions take a pivotal role in an energy system's transition toward an increased share of renewable energies. The technological and economic factors come together in energy system transformation, as they guide the directions of possible PED pathways depending on technologies required and investments available.

However, significant investments required for the energy transition (especially, in economically poor areas) may contribute to an increase in energy poverty and in disparities between different income groups of end-users [3]. Therefore, in order to preserve the balance in wealthy and impoverished areas, a combination of targeted policies is important. More specifically, technological solutions must be accompanied by policies that financially allow their implementation in all parts of society. The complementarity of sub-systems (technologies-institutions) can allow the balance in the energy transition in diverse areas. As such, the affordability of the energy transition should be considered in developing solutions for PED implementation.

Energy system transformation is only feasible with the presence of the social aspect that, in this study, refers to interactions of individuals based on their norms and values. Social dynamics are complex in the sense that they are dependent on socio-cultural context and socio-psychological context [38] and increasingly important for the modern energy systems while they drive the path to PEDs [24]. These contexts incorporate social identity, trust-building, and power relations. They deserve more attention in understanding the social system but have been underestimated and simplified in energy transition studies [38]. In practice, it can be observed, that most of the representative examples of PEDs are initiated and led by the citizens that demonstrate a bottom-up approach where social identity, trust-building, and power relations played a fundamental role.

In the energy transition, the key role is played by the end-users [39] as they are the stakeholders for whom this transition is primarily being held, who will make decisions and act based on their motives and social-value orientations. Thus, their roles and behavioral patterns are central for developing energy transition accordingly. In regulating the energy transition, the governments and policymakers take the leading role.

Altogether, the PED concept has been developed to mitigate environmental challenges such as climate change and CO_2 emissions. With the purpose to reduce CO_2 emissions, the PED concept focuses entirely on renewable energy generation. To eliminate dependence on fossil fuels, a combination of spatial, techno-economic, and social solutions should be developed where a central mission is CO_2 emissions reduction [40].

5.1.3. Doughnut Economics view on PEDs

As PEDs focus on the environmental and social goals, they are well aligned with the view of Doughnut Economics (or Doughnut for short). This framework proposes viewing the system we are living in holistically pursuing two goals: (1) to not exceed the ecological ceiling by exhausting the natural resources, and (2) to ensure that everyone's needs are met by creating socially just space for humanity [22]. This innovative model is based on the coherence between economic policy, environmental and social issues assuming that agents' actions are interconnected [41]. Therefore, the integration of the Doughnut vision into CAS can contribute to achieving the goals of PEDs.

When applying the Doughnut to the energy domain, the main social foundation to consider is access to energy, while the ecological ceilings are climate change and air pollution. As such, the PED Doughnut is the safe zone between these two extremes, which represents the ability to thrive economically. In order to remain in this PED ring framed with the Doughnut boundaries, the focus must be on basic principles such as reducing, reusing and producing. More specifically, reducing energy consumption based on fossil fuels and reusing are efforts to reduce CO_2 and avoid environmental degradation, while producing renewable energy and redistributing it are efforts to create access to clean energy for all and allow social inclusion and energy justice.

Importantly, Doughnut Economics has been developed with the focus on *distributive* (i.e., sharing with others the value created and redistribute it to improve equity amongst the users) and *regenerative* (i.e., promoting circularity of resources) dynamics. These dynamics are central for energy systems to tackle challenges and shift from unsustainable to (more) sustainable. PEDs can be exposed to disruptions, whether due to climate change, COVID-19, or renewable energy-related issues. Designing resilient systems is crucial for a successful energy transition where the system can not only be resistant to disruptions and can quickly restore after a disturbance [42], but also ensures socially just space. Hence, robustness should be comprised in the PED concept with the capacity of the energy system to tolerate disturbances while retaining its functions. This can be achieved through adaptability or transformability of the system: by adapting to the new circumstances preserving its basic features or by transforming to a new state creating new mechanisms to respond to disruptions [42].

Nevertheless, the understanding and application of the Doughnut framework in energy transition research and policy domains is still in an early stage. There are no studies that have applied this vision for the PEDs pathway. One of the frontrunners in the implementation of Doughnut Economics on a local level is Amsterdam [43]. However, its main emphasis is solely on circular economy. Thus, Fig. 3 illustrating CAS is intended as a call for further studies to pay more attention to incorporating the Doughnut view into the PED concept.

5.2. *Discussion of the PED concept's limitations and future research directions*

This comprehensive view on PEDs includes new lenses such as the complexity of the system and the Doughnut approach, through which PED implementation can be viewed and guided. These novel ways of approaching the energy transition bring comprehensiveness and resilience of PEDs into focus. Nevertheless, there are several limitations in the PED concept that merit more attention, and their integration can contribute to achieving far-reaching PEDs.

One of these is technologies' after-lifetime emissions. Technologies used for generating and storing renewable energy such as photovoltaic solar panels, wind turbines, and energy storage batteries are not completely renewable, since they create a negative environmental impact after their lifetime (average 25–30 years – solar panels and wind turbines, 10–20 years – energy storage batteries) [44]. Additionally, the mining of minerals for lithium-ion batteries also contributes to environmental degradation and this impact spreads beyond the area they are used in. However, the impact is still minor when compared to that of fossil fuel-based energy. Most components of these technologies are recycled or reused (approximately 90%) [45]. Even though the negative environmental impact of renewable energy technologies is relatively insignificant, the emissions produced should be taken into account in assessment metrics to cover the full life cycle of PEDs.

Furthermore, the existing PED concept does not include electric mobility and its energy demands, which remains an important knowledge gap. Electric mobility has been recognized as one of the solutions for mobility transitioning to renewables. By its nature, electric mobility creates two main benefits: (1) it contributes to the reduction in CO_2 emissions, and (2) it emerges as energy storage [46]. As energy-consuming technologies, electric vehicles (EV) create additional electricity demand. This means that more electricity should be generated in order to satisfy this demand. However, despite an increase in electricity demand, emissions can still be reduced if there is a substantial change in energy infrastructure. Another function of electric mobility, energy storage, can boost the flexibility of the energy system and stability of the grid by shaving the peaks of power. EV storage batteries enable to store and reuse of the energy that is generated when the demand is low [47]. It means that a significant electricity storage capacity would be available with all these batteries on wheels [48]. However, infrastructure-related issues such as the installation of more smart charging points for EVs remain a concern. Given the expected rise of electric mobility and PEDs, more research on these issues is imperative.

Zooming in on the real-life PEDs, these are clearly path dependent. While sharing some similarities such as energy self-sufficiency, social cohesion, reliance on a combination of innovative technologies, a partnership of stakeholders, and created sustainability values, the PED examples reveal significant differences [23,24]. First, they vary in their geographical scale –a neighborhood, a district, an island. This demonstrates that a PED should not be tied to the term "district" and restricted to this unit, but rather should be flexible in delineating the scale as long as it satisfies the requirements of the PED concept and allows to create PEDs in a different (smaller or larger) geographical scale. Second, the PEDs differ in their targeted stakeholders and contextual factors. Targeted stakeholders of the given examples vary from end-users (who later become prosumers[11]) to social housing cooperatives and residents (tenants). Contextual factors such as built or newly built buildings, available renewable energy sources, required financial investments, awareness of citizens and readiness for technology adoption, local policies and regulations make the PED examples distinctive. Evidently, there is no one-size-fits-all solution for the implementation and replication of PEDs.

Accordingly, the future research directions of PEDs should include the following:

- ○ Incorporating the Doughnut view into the PED concept with the aim to comprise the full life cycle of the energy system with regenerative and distributive dynamics of resources that contributes to resilience of the system.
- ○ Investigating electric mobility, as it is a promising but underdeveloped area related to energy transition and PEDs with high potential to contribute to carbon emissions reduction and providing (additional) portable energy storage.
- ○ Applying a bottom-up approach in studying PEDs, as they are flexible in delineating the physical scale and have a better chance to be implemented locally first, and then have an impact globally.

6. Conclusion

Reviewing the PED and similar concepts and comparing them to the real-life PEDs reveal substantial knowledge gaps and limitations of the concepts. First, there is a lack of consistency between PED and similar definitions and concepts that often causes misinterpretations. Inconsistency also occurs in the assessment metrics across the existing PED-related concepts. Second, being too simplistic, the concepts fail to consider the contextual factors that are inherent in the real-life PEDs. Contextual factors make PEDs path dependent and can explain

[11] Energy users who generate renewable energy in their domestic environment and either store the surplus energy for future use or trade with interested energy customers in the smart grid [49].

deviations. This also means that there is no one-size-fits-all solution for PEDs. Third, energy flexibility can only be achieved through dynamic and virtual PEDs, and hardly through autonomous ones. The existing concepts are too idealistic and ambitious in constructing the image of PEDs as autonomous, and they fail to consider the features of modern urban areas such as high population density, space scarcity, and limited availability of renewable energy. Therefore, the extended interaction of PEDs with the neighboring districts or virtual power plants, which makes PEDs dynamic or virtual, is more successful in achieving flexibility as observed in the practical examples of PEDs. Fourth, the assessment of the technologies' after-lifetime emissions is not included in the PED metrics. As the technologies are not completely renewable, even though their emissions are relatively insignificant, this is a knowledge gap that is essential to be considered to cover a full life cycle of PEDs.

This study significantly contributes to the literature, as it has developed a comprehensive view on the PED concept and integrated the CAS and Doughnut Economics views into PEDs. This has not been previously explored, though it can be essential to boost the local energy transition since these two frameworks enrich the PED concept by comprising the complexity and resilience of PEDs. A necessary route for future research is electric mobility that should be studied more extensively and included in the PED concept, as it can contribute to solving a pressing problem of energy storage. Another promising direction for future studies is integrating the Doughnut view into the energy transition and specifically PEDs. The application of this view in PEDs can contribute to a desired future energy system that is climate-neutral and resilient by incorporating regenerative and distributive dynamics.

Policy recommendations for future development of PEDs include the following:

- PEDs should be developed using area-based approaches that aim to include all groups of end-users and diverse areas. The area-based approach means allowing different combinations of policies that would target specific groups in PED development taking into account their local (spatial) contexts. Specifically, the policies should have two main branches – financial and social. While the first branch addresses the financial leverage in energy transition such as imposing taxes (suitable for wealthier regions) or offering subsidies and loans (targeting more impoverished regions), the second branch shall focus on encouraging local energy initiatives and supporting collaborations (e.g. through organizing information campaigns, creating knowledge exchange platforms). Socially-oriented policies are important, as initiative and collaboration of different stakeholders have been proven by the examples to be fundamental in developing successful PEDs.
- Emphasis should be given to electric mobility and its benefits. However, there are also (financial) challenges in transformation to electric mobility. Therefore, in order to make the transformation smoother, the policies shall target (especially) vulnerable groups through providing alternatives or supportive conditions that would allow affordability and inclusion.
- Development of dynamic and virtual PEDs should be prioritized over autonomous ones especially in modern urban areas that face challenges such as high population density, space scarcity, and limited availability of renewable energy. The dynamic and virtual PEDs allow flexibility through interacting with neighboring PEDs and VPPs. As observed in the practical examples, this can lead to successful implementation and sustainability of PEDs.

Author contributions

Conceptualization, Methodology – E.D., S.H.V., G.J.H., E.v.L.; Formal analysis, Writing – original draft, Visualization – E.D.; Supervision, Review & editing - S.H.V., G.J.H., E.v.L. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

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

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