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Economic, social, and environmental aspects of Positive Energy Districts—A review

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Abstract

The concept of Positive Energy Districts (PEDs), introduced in the Strategic Energy Technology Plan, is one of the fundamental approaches for a successful, clean and sustainable urbanization by 2025. According to the European Commission, a PED is a set of buildings where the community controls the energy flows and aims at a net positive energy balance over a year by utilizing renewable energy sources. There are a plethora of concepts similar to PEDs, such as Positive Energy Community, Net Zero Energy Neighborhood, Plus Energy Districts, that create a need to establish a structure that can facilitate the definition, development, and precise identification of PEDs. Thus, this paper aims to fill this research gap by comparing these and other related concepts through a critical literature review based on three pillars composing the triangle of sustainability: economic, social and environmental. By doing this, the paper aims to determine the connections between these similar concepts, homogenize the use of terms and avoid the issue of repetitions, which can help draw lessons learnt from other energy-savings concepts. This study shows how PEDs and Nearly Zero Energy Communities have similar bases, aims and omissions. They diverge in a few key concepts, which can become learning points for PEDs.

This article is categorized under:

Climate and Environment > Net Zero Planning and Decarbonization
Policy and Economics > Energy Transitions
Human and Social Dimensions > Energy and Climate Justice

KEYWORDS

energy justice, NZEB, net zero energy community, Positive Energy Districts, triangle of sustainability

Abbreviations: BEV, Battery Electric Vehicle; EIP, European Innovation Partnership; EPBD, Energy Performance of Buildings Directive; ES, Electrical Storage; GHG, Green House Gases; ICT, Information and Communications Technology; MESS, Multi Energy System Simulator; NOx, Nitrous Oxide; nPEF, Non-Renewable Primary Energy Factor; NZEB, Nearly Zero Energy Buildings; NZED, Net Zero Energy District; NZEN, Net Zero Energy Neighborhood; PEB, Positive Energy Blocks/Positive Energy Buildings; PED, Positive Energy Districts; PEF, Primary Energy Factor; PM, Particulate Matter; RES, Renewable Energy Sources; SC, Smart City; SET-Plan, Strategic Energy Transition Plan; SOx, Sulfur Oxide; TS, Thermal Storage; ZEC, Zero Energy Community.

1 | INTRODUCTION

In 2019 the household sector accounted for almost 27% of the final energy consumption (Eurostat, 2019), making it one of the most attractive target sectors to reduce energy consumption. In 2014, nonresidential buildings accounted for 25% of the total European floor area (European Commission, 2014). Adding to this, BUILD UP stated in 2019 that specific energy consumption in nonresidential buildings is at least 40% higher than in the residential sector (BUILD UP, 2019). For this reason, numerous attempts have been made to establish frameworks that would facilitate the energy transition and help achieve the European and global climate goals. One of the most recent of such frameworks (or "concepts", as we refer to them throughout this article) is Positive Energy Districts (PEDs). The Strategic Energy Transition Plan (SET-Plan) first introduced it in 2018 (SET-Plan Working Group, 2018). Its definition has evolved to "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" (JPI Urban Europe, 2020). However, it distinguishes itself from other concepts (including Net Zero, nearly Zero, Plus Energy, and Emission Districts/Neighborhoods) by its more holistic approach that includes social concerns, inclusiveness and energy poverty (Good et al., 2017; Hedman et al., 2021). As there is a richer body of research on at least technical aspects of achieving energy savings on a neighborhood or community level (Ala-Juusela et al., 2016; Amaral et al., 2018; Carlisle et al., 2009; Koutra et al., 2017; Marique & Reiter, 2014; Sørnes, 2017), PEDs can profit from the previous studies. This paper analyzes and points out the differences and similarities between PEDs and other approaches and aims to:

1. provide a thorough analysis of the definition of PEDs and other similar concepts (mainly, NZEC/NZED) concerning economic, environmental, and social aspects and
2. determine the connection between PEDs and other similar concepts to bring a new light into this field of research, avoid repetition and homogenize the use of terms.

Table 1 shows the main concepts of the article and their respective primary reference. This study utilizes the three pillars of sustainability (Social, Economic, and Environment) to analyze PED. This system can enable an interdisciplinary approach (Campbell, 1996; Purvis et al., 2019), which is essential given the intrinsic holistic nature of PEDs. Based on this approach, a "Triangle of sustainability" is built similar to the work of Bakari (2021). The remaining paper has the following structure. Section 1.1 discusses the chronological evolution of PEDs and other similar concepts. The methodology Section 2 justifies the various dimensions of investigation for the district concepts derived from the three pillars of sustainability. Section 3 applies these dimensions to evaluate each concept accordingly to unveil similarities and differences. Finally, Section 4 discusses the findings and connects them with the aims mentioned above in the paper.

1.1 | History

The first concerns about households' expenditure started to appear in the literature during the early 1970s (Wessling Jr., 1974), in conjunction with the first oil crisis. However, the first actual increase in publications containing

TABLE 1 Major literature used in this paper for each concept

Concept name	Abbreviation	Literature
Positive Energy District	PED	JPI Urban Europe (2020), SET-Plan Working Group (2018)
Positive Energy Block	PEB	Cartuyvels (2021)
Zero Energy Community	ZEC	Carlisle et al. (2009)
Net-Zero Energy Neigbourhood	NZEN	Marique and Reiter (2014)
Net-Zero Energy District	NZED	
Positive Energy Building	PEB	Magrini et al. (2020a)
Nearly Zero Energy Building	NZEB	

methodologies to improve residential buildings' energy performance came in 1979. The initial designs focused mainly on improving thermal efficiency and lowering heat demand in buildings through solar gain and thermal storage. Some of the methods utilized were solar thermal panels, Trombe walls, thermal wall storage, to mention some (Block & Hodges, 1979; Casperson & Hocevar, 1979; Kieffer, 1979; Lee, 1979; Munday, 1979; Nichols & Nichols, 1979; Noll et al., 1979; Plumb, 1979; Tymura, 1979). With time the focus shifted toward superinsulation. In the 1990s, the Passive House concept was established. It embraced superinsulation completely as a cornerstone of its design, together with controlled air ventilation and carefully designed solar gain and shadings (Schnieders et al., 2015). A similar approach is that of Nearly Zero Energy Building (NZEB). The concept has many different variations regarding methodologies and design for calculation. Still, high-efficiency materials and local renewable generation are necessary due to the high thermal efficiency required (Petcu et al., 2017). The European Union has included its own definition of NZEB in the Energy Performance of Buildings Directive (EPBD). It states that "Nearly Zero Energy Building" means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby (European Parliament, 2018). The last amendment to the EPBD states that all governmental and public buildings will have to be NZEB by 2018, and starting from the year 2021, all new buildings of any nature will have to be NZEB (European Union, 2010). However, the Member States' detailed implementation of NZEB definition is being done with different indicators, methods, and calculation procedures. Some Member States have a numerical indicator of specific primary energy use requirement to qualify as NZEB, whereas others do not. Analogously, not all Member States mandate any requirements regarding renewable energy (BPIE, 2021). With an even stricter energy balance, Positive (or Plus) Energy Buildings (PEBs) are a direct evolution of NZEBs. However, while the European Commission firstly proposed the concept of NZEBs in the EPBD, PEBs already existed before that time. As Cole and Fedoruk (2015) defined it, a PEB produces more than it can use and exchanges that energy where it is most needed. They consider both electricity and heat exchange as a possibility. In 2009 the NREL published "Definition of a Zero Energy District" and defined a Zero Energy Community (ZEC) as "one that has greatly reduced energy needs through efficiency gains such that the balance of energy for vehicles, thermal and electrical energy within the community is met by renewable energy". Although the paper provides concrete definitions and measures, the term community still remains vague.

Several studies support broadening the boundary from a single construction to a district level. By assembling different building and end-users typologies, it is possible to reduce district heating and cooling costs. At the same time, different demand patterns can help to shave the load curves and reduce and move peaks (Paatero (2009), Koch et al. (2012), Pachauri and Reisinger (2008)). In 2014, Marique and Reiter (2014) proposed smaller units called "urban blocks" that would compose a whole district. In a similar fashion, PEDs would also be composed by PEBs.

In 2017, the discussion veered over to PEDs, when Nzengue et al. (2018) presented a method for archetyping districts and facilitating the implementation and replication of large-scale refurbishment plans within the Sinfonia project. This article refers to PEDs as Low Energy Districts and sees PEDs as a way of achieving a Smart City (SC). Although the idea of SCs has evolved according to different needs and goals that equally evolved through time, there is a strong link between PEDs and SCs. The European Innovation Partnership (EIP) on SCs and Communities defines a SC as a "system of people interacting with and using flows of energy, materials, services and financing to catalyse sustainable economic development, resilience, and high quality of life" (European Innovation Partnership on Smart Cities and Communities, 2013). The EIP ambition is to use these concepts to develop and transform current districts into "zero/plus energy/climate-neutral status" by integrating local renewable energy technologies through smart energy networks, virtual power plants, storage systems, and demand control. Hence, SCs are a means to achieve "energy positivity" and not PEDs per se. PEDs might achieve energy positivity/neutrality from renewables by drawing from knowledge developed through the years in the frame of SCs. Figure 1 points out the significant milestones and summarizes how energy savings concepts have evolved towards PEDs.

2 | METHODOLOGY: CRITERIA FOR ANALYSIS OF THE CONCEPTS

In order to analyze the PEDs and their similar concepts according to technoeconomic, environmental, and social criteria, those three pillars of sustainability will have to be broken down into relevant subthemes. Therefore, as proposed in Bakari (2021), a sustainable development triangle approach is used, to account for the three pillars holistically. Figure 2 shows the selected criteria of analysis included within the three main pillars.

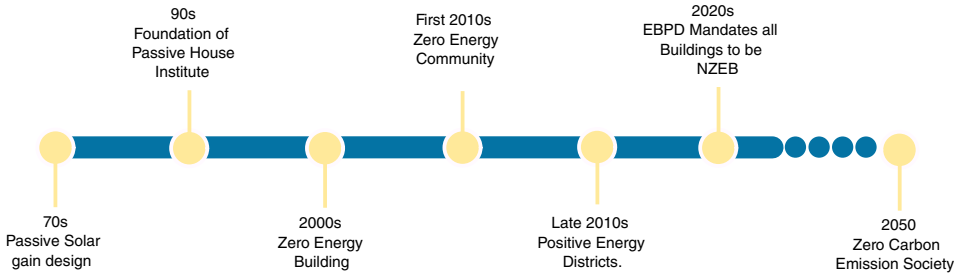

FIGURE 1 Path towards positive energy districts

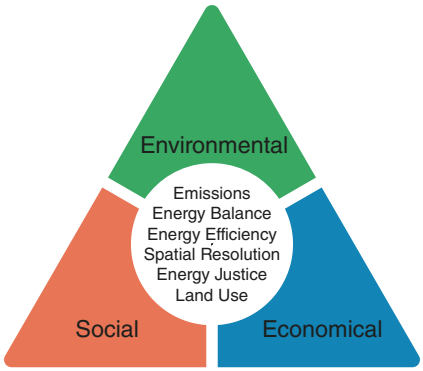

FIGURE 2 Criteria of analysis within the triangle of sustainability

All of the six criteria of sustainability relate to each pillar of sustainability. Spatial aspects have repercussions on the economics of a project, the environmental and social impacts. Similarly, this is true also regarding emissions, land use, energy balance, efficiency and justice. Section 3 discusses these aspects in more detail. The authors are aware that other factors such as costs, policy interventions, and governance, to mention a few, can influence the development and the diffusion of PEDs or other similar concepts. It is also clear how policy interventions and governance are strongly related to social concerns while total costs also connect to economics. On the other hand, costs can vary significantly between sites and projects. Lindholm et al. (2021) studied the availability of renewable energy potentials between different countries in Europe and their associated costs. Governance and policies are also strictly connected to countries. As this study aims to enable a comparison between different energy concepts, the choice was limited to the criteria listed in the following sections. These criteria are less dependent on geographical location and countries, thus allowing a more direct comparison.

Mobility is another aspect that has not been considered as a single criterion, but that requires additional clarification. Mobility is a cross-sector aspect that touches many of the criteria selected in this work. For this reason, it has been decided not to include it singularly but to encompass it in those criteria such as emissions and energy balance, where it has a stronger influence. On the one hand, it is possible to consider electric vehicles as a load or a storage option in the energy balance calculation. On the other hand, mobility is one aspect that highly contributes to the general emission of an urban area.

The general application of each criteria in the context of this work is explained in the following section.

2.1 | Spatial resolution

As highlighted by Pfenninger et al. (2014), the spatial dimension is one of the challenges of modeling the current energy transition efficiently. On the one hand, this is related to the characteristics of renewable energies that require a high degree of spatial granularity (Martínez-Gordón et al., 2021). On the other hand, the growing decentralized nature of the energy system of urban locations (Weinand et al., 2019) makes the understanding of the spatial dimension fundamental. Characterizing the energy system of urban locations means knowing the technologies used in it and implies understanding the boundaries of the investigated system. Among others, The National Institute of Building Sciences (2015) refers to the boundaries of the site when talking about whether renewable energy should be collected and generated

within the boundaries of the system or not. Hence, knowing and understanding the spatial resolution and the boundaries of the system, is essential at urban level analysis to properly characterize the energy balance and efficiently plan the deployment of renewable energy sources (RES). This paper analyzes the spatial resolution of the different concepts, whether they apply at a building, a block, or a district level.

2.2 | Energy balance

One key aspect that all previously mentioned concepts have in common is the system's energy balance. Depending on the concept, this can vary from single buildings over blocks to entire districts. The energy balance criteria encompass the energy exchange across system boundaries, types of energy included, and energy flexibility. The criteria are motivated by an ever-growing urbanization movement and the associated high geographical density of energy demand combined with a low generation (Grubler et al., 2012). Additionally, more "uncontrolled" renewable generation and high power demands such as fast electric vehicle charging will strain the power grid. Flexibility, for example, provided by prosumer districts could help stabilize the electricity grid (Neetzow et al., 2019). Thus, the energy balance with the outer scope[1], and flexibility, are important factors to consider within urban district concepts. The temporal resolution, the energy metric (primary energy or final energy), the energy type (e.g. electricity, heating or cooling), and the incorporated end-users are also influential to the energy balance. Hence this work compares the concepts' definitions according to:

- **Balance:** If the energy balance with the surroundings needs to be positive, zero or nearly zero
- **Temporal resolution:** The temporal definition of the energy balance, for example, annual
- **Calculation basis:** The energy metric that the balance is based on, for example, primary energy

2.3 | Emission

Environmental aspects, such as Greenhouse Gas (GHG) and Particulate Matter (PM), strongly correlate to the aforementioned energy aspect. Almost 80% of the EU's GHG emissions in 2017 are related to energy supply and demand, including the energy industry itself, nonmobility associated fossil fuels and the mobility sector (European Commission, 2020). Finally, another factor related to local health is PM_{10} and $PM_{2.5}$ emissions. In 2016, the daily EU thresholds for PM_{10} and $PM_{2.5}$ exposure exceeded for 13% and 6% of the urban population in EU-28 countries, respectively (European Environment Agency, 2018). Finally, environmental aspects can be divided into local and global impacts. Local impacts include specific particulate emissions such as PM_{10} and $PM_{2.5}$ but also water and soil pollution, or odor and noise impact. Global impacts encompass GHG emissions but also raw materials. Often the central focus is given to GHG emission reduction, and therefore the local impact is neglected. However, local aspects should be of high importance, especially in housing and district concepts. Further emissions that could be included are so-called gray emissions related to the production and mining of raw materials.

2.4 | Land use

As free space in dense urban areas is scarce, land use is a critical criterion as there will always be a trade-off between some of the three pillars of sustainability. For example, the available space for energy generation and social activities needs to be well balanced. This balance includes evaluating the best usage of land for the benefit of the community before implementing an energy district-related project. As part of their urban data platform, the European Commission states as one of their key messages how the distribution and usage of public spaces need optimization and inclusiveness (European Commission, 2019). Of course, this also applies to shared private spaces such as rooftops or basements.

2.5 | Energy efficiency

The energy efficiency of the building stock has a decisive role regarding the energy transition. In 2018, the residential sector accounted for about 26% of the total final energy consumption in Europe (Eurostat, 2018). According to Deloitte,

in 2014, all buildings accounted for 39% of the total final energy consumption. Meanwhile, 75% of the European building stock is old and inefficient and the rate of renovation is going at a too low pace to meet future environmental standards (Deloitte, 2016). As of 2018, heating and cooling amounted for most of the energy expenditure in European households covering almost 80% of the total, when domestic hot water is considered (Eurostat, 2018). At the same time, 32% of the energy supplied to buildings comes from natural gas. Regardless of how heating and cooling are supplied, whether via electricity (i.e. heat pumps) or gas, the current situation represents a difficult challenge and needs addressing. Achieving a positive energy balance will require low energy consumption in the first place. While it contributes positively to the environment, a PED would not be feasible with efficiency improvements alone. Even though there are various aspects related to energy efficiency, this work considers only those aspects related to the building and its associated infrastructure (e.g. at district level). Other aspects such as appliances and processes were not considered individually because they can be considered part of the building and infrastructure.

2.6 | Energy justice

When referring to the energy transition, the focus is often on technical and economical aspects. However, capturing the human dimension of an energy system is of the same importance (Pfenninger et al., 2014). Additionally, the European Commission aims at achieving a fair, just, and inclusive energy transition (Bouzarovski et al., 2020). In a nutshell, this means that the energy transition should not leave anyone behind. Thus, attention should shift to those whose livelihoods rely on the fossil fuels industry and to the more vulnerable people. It is essential to allow the latter to access the implemented measures to live in less vulnerable conditions. Moreover, the energy transition should include everyone, regardless of gender, income, or education. Equal access to an essential commodity, such as deciding to have an adequately warm house, is fundamental. The energy transition presents in this context barriers and opportunities. Walker and Day (2012) argued that fuel poverty is about distributing access to energy services, providing warm houses, and being free from avoidable diseases. The European Union usually refers to fuel poverty as to energy poverty, whose causes and consequences mostly coincide (Bouzarovski, 2014). Lack of money is a central issue, but it is not the only problem. Intrinsically tied to lower incomes, high energy prices play an important role as well. In terms of heating and appliances, the low energy efficiency of houses raises further concerns, pushing energy bills further high in an environment where capital is already lacking. Because vulnerable groups often do not have the means to renovate and retrofit their apartments, they are usually more prone to live in lower efficiency buildings.

3 | EVALUATION OF THE CONCEPTS AND DISCUSSION

Basing the analysis on the sustainable triangle approach allowed identifying some major areas of interest that help in defining commonalities and differences that different concepts have compared to PEDs.

Table 2 provides an overview of the main differences and similarities of the various analyzed concepts based on the selected criteria.

One can see a strong correlation between a lot of the concepts analyzed. NZEC, PEB, PED, and NZEN are all very similar. The major distinction lies in the energy balance and energy justice. While PED requires an annual positive energy balance by definition, the other concepts only expect a zero or nearly zero balance.

Figure 3 further shows an hierarchical representation of the different concepts considered in this work as the results of the analysis performed. As one can see, the PED concept stands on top of this upside-down pyramid because it includes all the aspects and attributes considered. Then, the concepts are sorted as they gradually do not consider some attributes. Zero Energy Communities differs from PED because of the balance, but they also miss energy justice aspects. On the other hand, while PEBs have a positive balance, they are not dealing with land use considerations. Finally, the concepts at the bottom of the pyramid only consider emissions and overall efficiency neglecting land use and energy justice. Additionally, some of them only relate to a single building rather than a district scale.

Although the above-mentioned methodology aimed at classifying and categorizing the different concepts, it is clear from the results that there is not always a clear distinction between them. Therefore, it is vital to discuss and be aware of the challenges of dealing with multiple concepts. As for the categorization, the challenges are interdisciplinary and go from technical challenges to those related to social/human aspects.

TABLE 2 Concept categorization

		Energy balance						
Abbreviation	**Spatial**	**Balance**	**Temporal**	**Calculation basis**	**Energy efficiency**	**Land use**	**Emissions**	**Energy justice**
PED	District	Positive	Annual	Primary Energy	B + I	S	GHG	x
PEB[a]	Block	Positive	Annual	Primary Energy	B (+ I)	—	GHG	x
ZEC	District	Zero	Annual	Multiple	B + I	E + EN	GHG, O	∼
NZEN	District	Zero	Annual	Primary Energy	B	—	GHG	—
PEB[b]	Building	Positive	Annual	Primary Energy	B + I	—	GHG	—
NZEB	Building	nearly Zero	Annual	Primary Energy	B	—	GHG	—

Abbreviations: ∼, only mentioned; B, Building Efficiency; E, economic; EN, environmental; GHG, Greenhouse gases; I, Infrastructure Efficiency; O, $NO_x + SO_x$; PM, particulate matter; S, social.
[a]Positive Energy Block.
[b]Positive Energy Building.

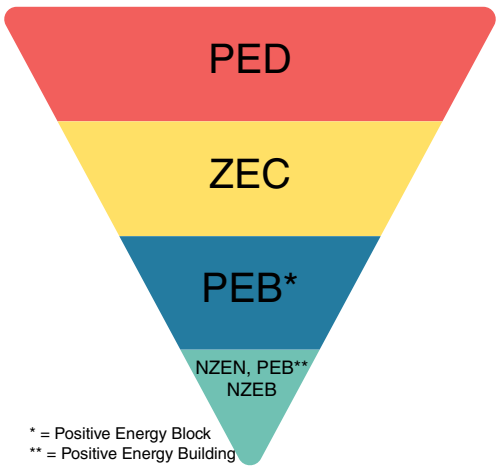

FIGURE 3 Hierarchical representation of the analyzed concepts according to their attributes

3.1 | Spatial resolution

As one can see from the results in Table 2, most of the concepts analyzed relate to the spatial dimension. By talking about small scale urban areas such as districts or communities, geographical boundaries are essential to understand what is inside or outside of a given system. PEDs exploit this aspect due to the various definitions currently in place. Lindholm et al. (2021) present the three definitions of Autonomous/Dynamic/Virtual PED that all include considerations with a geographical nature. These are mainly related to PED's boundaries and whether technologies must only be located within the boundaries or can also be outside the district. More precisely, Autonomous PEDs have a well and strictly defined geographical boundary. They are entirely energy independent and cannot import energy, although they can export. Hence, Autonomous PEDs have to meet all their energy demand internally. A Dynamic PED also has clear geographical boundaries. It can export and import energy as long as the overall balance remains positive throughout the year. The exchange of energy can happen between other PEDs or the external grid. Finally, Virtual PEDs have a geographical boundary, but they can also import and export outside of it. In Virtual PED, energy can be exported and imported, can also have renewable energy systems and storage outside the district's geographical boundaries, and thus the name is "virtual." Of course, the positive balance restriction applies here as well; therefore, the total amount of energy produced outside and within the district must be larger than the imported. These three spatial definitions of PED also affect the energy balance. An autonomous PED, for example, will have a strict positive balance at any time. In contrast, the other two will be allowed to have a momentary negative balance as long as the overall yearly total

remains positive. Thus, this also reflects on the temporal resolution considered for the energy balance. Lindholm et al. (2021) point out how, theoretically it could be possible, by properly combining the three kinds of PEDs to achieve a positive balance also at a larger scale. Additionally, JPI Urban Europe (2020) mentions that the terms "regional" and "local" have been left open to allow some flexibility. The complexity of the system of a district may lead to different boundaries for each end-user sector considered. In the report "Towards Nearly Zero Energy Buildings," Hermelink et al. (2013) describe the characteristics related to the system boundaries and they present how this has been considered in different cases around Europe. They point out how the system boundaries' definitions are needed to understand the available renewable energies options: on-site PhotoVoltaic (PV) or renewables, nearby installation financed by user or off-site renewable like a biomass power plant. Additionally, they further exploit the analysis by also consider eventual power purchase agreements. Furthermore, Hermelink et al. (2013) exploit the difference between system and physical boundaries. This refers to whether we are talking about a single building, a cluster of buildings or a city. Article 2.2 of the EPBD (European Union, 2010) defines NZEB as a building where *"nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby"* which means that also off-site renewable generation is allowed. Carlisle et al. (2009) mentioned that when talking about energy communities, except for the case of islands, the boundaries are arbitrary and can be either geographically but also politically defined. The National Institute of Building Sciences (2015) defines the site boundaries as the *"Line that marks the limits of the building site(s) across which delivered energy and exported energy is measured."*

Figure 4 shows a possible spatial structure of a PED. In this example, each building is a PEB. Two or more PEBs produce a PEB, which themselves form a PED. Each specific resolution can produce more energy than it needs and export to other buildings, blocks and districts. Each block or district can contain a variety of different end-users, including industrial, commercial and residential buildings.

3.2 | Energy balance

According to JPI Urban Europe (2020), one of the primary goals of PEDs is to have a surplus of renewable energy generation. Notably, it states that the surplus should be on an annual basis and either at a local or regional level. Hence, it is essential to understand the exchanges between the different grids and buildings in a PED to properly calculate the energy balance (Bottecchia et al., 2022). In this sense, Figure 5 presents the interaction within these entities as well as within storage options in the case of a PED.

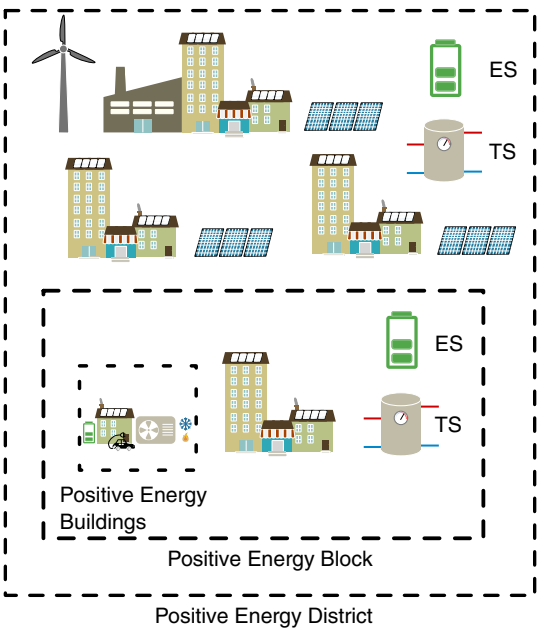

FIGURE 4 Spatial resolution for positive energy districts. ES, electrical storage; TS, thermal storage

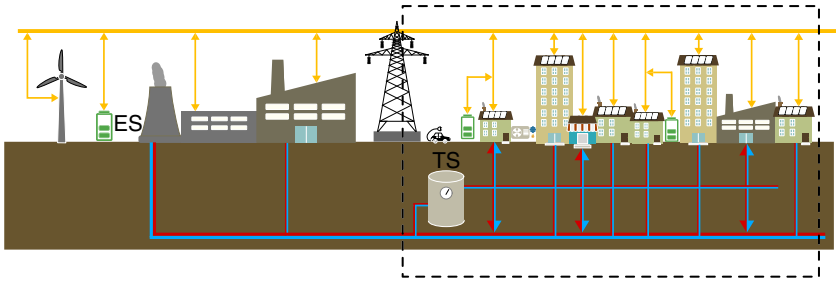

FIGURE 5 Possible energy exchanges between electrical grid, district heating, and buildings in a positive Energy District. The dashed lines indicate the physical and grids border of the PED. ES, electrical storage; TS, thermal storage

Given the complexity of the system examined, flexibility options are another key focus point. Thus, through demand-side management, storing energy and coupling of sectors, the PED serves the grid with the flexibility to achieve a resilient regional energy system. Similarly, PEBs should produce more energy than they consume on a yearly basis (EIP-SCC, 2018). Both concepts, PEDs and PEBs, calculate with primary energy. An official calculation methodology, including equations, is not established. Thus, Gabaldón Moreno et al. (2021) propose a calculation methodology for achieving PED status. The most important steps are to obtain the energy use, the local generation, the imported energy, the conversion to primary energy, and finally, calculating the PED balance. Nonrenewable primary energy factors (nPEF) are used, and for electricity export, the substitution concept has been adopted. The mathematically expressed PED condition is shown in Equation (1).

$$\sum_{\mathrm{ts}=0}^{Y}\sum_{c}^{C}\left(e_{c,\mathrm{ts}}^{\mathrm{im}}{}^{*}\mathrm{nPEF}\right) < \sum_{\mathrm{ts}=0}^{Y}\sum_{c}^{C}\left(e_{c,\mathrm{ts}}^{\mathrm{ex}}{}^{*}\mathrm{nPEF}\right). \tag{1}$$

Here, Y stands for year, ts for timestep, C for the vector of energy carriers, c for a specific energy carrier, e for Energy, im for import, ex for export, and nPEF stands for nonrenewable primary energy factor (PEF). Final energy included in the PED concept and therefore also in the energy balance is electricity, heating, and cooling (Gabaldón Moreno et al., 2021). Bruck et al. (2021) extend this approach to an annual primary energy balance with a dynamically changing total PEF, according to the current grid generation mix, as shown in Equation (2). Renewable energy has a PEF of one. Bruck et al. (2021) use the total PEF instead of the nonrenewable one to also account for imported renewable energy from the grid. The dynamically, hourly changing PEF gives the PED more flexibility to achieve energy positivity and more desirable import and export behavior Bruck et al. (2021) also show how limiting the amount of electricity a PED can export to the grid at a given time increases district flexibility and grid resilience.

$$\sum_{\mathrm{ts}=0}^{Y}\sum_{c}^{C}\left(e_{c,\mathrm{ts}}^{\mathrm{im}}{}^{*}\mathrm{PEF}_{\mathrm{ts}}^{\mathrm{im}}\right) < \sum_{ts=0}^{Y}\sum_{c}^{C}\left(e_{c,\mathrm{ts}}^{\mathrm{ex}}{}^{*}\mathrm{PEF}_{\mathrm{ts}}^{\mathrm{ex}}\right). \tag{2}$$

The PEF of the exported energy (required to be renewable in PEDs) is set equal to the PEF of the most expensive energy technology on the marginal cost curve of generation at each time step. This is because the exported energy would substitute the most expensive energy generation at a given time. On the other hand, the average PEF of all technologies contributing to the generation mix is taken for imported electricity.

The energy balance also characterizes other concepts, and it is mentioned in different forms. ZEC is a community with reduced energy demand, allowing RES to cover electricity, Battery Electric Vehicles charging, heating, and cooling demand. According to the ZEC hierarchy, energy efficiency improvements and demand reduction should come before renewable generation within the local boundary, renewable production out of the community boundaries and purchase of off-site renewable energy certificates. Taking this hierarchy into account, there are four different ZEC classifications. Finally, the ZEC concept allows for four specific accounting methodologies to achieve net-zero energy performance. Those are "Site Energy", "Source Energy" which refers to primary energy, "Energy Cost" and "Energy Emissions". ZECs do not specifically focus on flexibility services to the grid (Carlisle et al., 2009). NZENs/NZEDs follow a multi-

energy approach and are the only concepts discussed that encompass mobility in the energy balance. Also in this case, primary energy is taken as an indicator for comparison among different energy types (Marique & Reiter, 2014). PEDs also consider electric and green mobility, although their role in the energy balance it is not explicitly stated. Finally, NZEB and PEBs also include electricity, heating and cooling and use primary energy as an instrument for comparison. The three pillars of sustainability are mentioned explicitly in the PEBs concept (Magrini et al., 2020). One factor that separates PEDs from the other concepts is the possibility of a virtual district. This requires the support of aggregators that create the virtual PED by aggregating its individual prosumers and trade the energy on the market. Autonomous and Dynamic PEDs, as well as the other concepts, do not rely on aggregators but can opt to use the aggregator model.

Another important aspect is the balancing time considered. As all the concepts considered in this paper, the PED framework considers the energy balance at an annual level. A point of criticism of this calculation method would be strong variations of the balance throughout the year at a seasonal level and across the day. However, both approaches come along with a series of advantages and disadvantages. On the one hand, moving toward an hourly balance allows considering the fluctuation of RES and the variations of the demand throughout the day. At the same time, forcing the balance to be positive each hour could result in costlier solutions and a nonoptimal grid utilization. On the other hand, an annual balance is more easily achievable, can require less computational power, and the integration of the grid may result easier. However, it also comes with some drawbacks since it does not take into consideration the seasonality of the demand and supply and the daily and hourly differences.

To overcome these issues, multiple approaches can be used. One would be to reduce the time perspective of the balance to, for example, 8 h as one third of a day. Another approach, as proposed by Bruck et al. (2021), is to restrict the grid exchange power to an acceptable value. For example, the grid capacity should not be surpassed or only by a small margin. A combination of both should ensure a more stable balance while simultaneously increasing grid resilience.

Additionally, it could be useful to include information on the share of own production used to cover the demand comparing it with import and export and another option could be to look at different time resolutions. Bottecchia et al. (2021) compare a novel tool that simulates the energy system of a district, called Multi-Energy System Simulator, with an existing optimizer. The study also shows the differences at a monthly level. A seasonal or monthly temporal resolution can provide valuable insights regarding the district by showing how local production compares to the import/export of energy.

3.3 | Emissions

A PED is required to have an annual net-zero GHG emission balance JPI Urban Europe (2020). The PEB concept does not encompass any emission goals or restrictions, apart from passively focusing on renewable energy generation (Cartuyvels, 2021). One of the four ZEC calculation approaches is net-zero energy emission. In this approach, the community would need to generate at least as much energy from zero-emission resources onsite as it would import or generate from emitting resources annually. Here, GHG, Nitrous Oxides and Sulfur Oxides (NOx and SOx, respectively) are mentioned as typical emissions. However, it is not further explained how they would be integrated in the annual balance. The remaining three approaches do not include emission goals actively (Carlisle et al., 2009). Also neither NZENs/NZEDs nor PEBs/NZEBs mention emission goals or constraints above the passive inclusion through renewable energy generation (Magrini et al., 2020; Marique & Reiter, 2014). Among many concepts, the PED is the only concept that explicitly includes a GHG emission balance as a requirement. However, considering the focus on renewable local energy generation of all the concepts, this goal is likely always implicitly included and fulfilled. In all cases, the active or passive inclusion of emissions is limited to global pollutants with a strong focus on GHG emissions.

3.4 | Land use

Although the adopted definition of PEDs does not consider land use aspects, most current PED or PED-like projects focus on how to utilize the land in terms of activities and end-use. The issue is mainly on how to manage common areas, commercial activities, recreational zones. The problem is not only of economic value (i.e. the number of sellable units) but also of social value. According to Hearn et al. (2021), in the case of Hunziker Areal, extensive citizen groups consultation happened during the years to this purpose, adding an important social dimension to the topic. Bossi et al. (2020) analyzed the current development of PED projects. They found that in their land-use typology mix, all had

residential use, 61% office, 22% industry, 61% commercial, 65% social and 30% other land use. Of these projects, 4% had one land-use typology, 57% a moderate mix (between 2 and 4), and 39% had five or more typologies (Bossi et al., 2020).

Net Zero Energy Communities have as main concern instead how to utilize brown and greenfields. In this case, the matter is to balance economics and energy efficiency. Brownfields are unsuitable for buildings and other human-related activities. A brownfield's economic value is lower than a greenfield, making them a better candidate for RESs installation. Furthermore, the land would be otherwise left unused. Brownfields are usually distant from the energy point of delivery, which causes some other difficulties in terms of energy transmission and loss of efficiency of the system (Carlisle et al., 2009). On the other hand, greenfields are close to or within inhabited centers, lowering transmission costs and related losses(Carlisle et al., 2009). The land's cost is higher, increasing the final energy cost and reducing the opportunity for social areas and real estate development. The latter might, in turn, discourage private development engagement. The considerations made in NZEC follow a more economical approach rather than social on this topic.

3.5 | Energy efficiency

In the context of the energy transition at the urban level, energy efficiency plays an important role. It is possible to refer to energy efficiency in relation to the characteristics of the building or of the infrastructure. As mentioned above, other aspects such as appliances and processes efficiency were not considered individually but as part of the building and infrastructure. Nevertheless, none of the investigated concepts provide quantitative indicators in relation to the efficiency level to achieve. Instead, qualitative aspects are considered across all the concepts analyzed.

In PEDs, energy efficiency represents one of the building blocks (SET-Plan Working Group, 2018). The high level of energy efficiency of the building envelope characterizes the PED concept as well as the use of active management of energy demand and the interaction with Information and Communications Technology (ICT) options to provide flexible options as long as these are economically viable options. Energy efficiency is also a pillar of the concept. However, in this case, there is a stronger focus on the efficiency of the building itself, focusing both on new built and retrofitting of existing buildings (Cartuyvels, 2021). Additionally, ICT solutions should allow reaching also the efficiency of the infrastructure. To achieve the status of a ZEC, energy efficiency represents the first solution concerning both the efficiency at the building level and the community level, thus the infrastructure one (Carlisle et al., 2009).

On the contrary, in NZEN, energy efficiency only relates to the building level with a strong focus on retrofitting and reducing consumption (Marique & Reiter, 2014). Magrini et al. (2020) depicts a similar approach in NZEB. This concept focuses on the building level and not on the community. However, suppose the aim is to achieve positive energy consumption. In that case, the efficiency of the infrastructure becomes an essential aspect (Magrini et al., 2020).

3.6 | Energy justice

Unlike other concepts analyzed in this paper, PEDs explicitly state the need for the energy transition to happen justly, shifting the focus from a mere technical perspective. The idea is reiterated often as citizen participation, citizen engagement, just transition, prevention of energy poverty, and other similar initiatives (JPI Urban Europe/SET Plan Action 3.2, 2020; Paci et al., 2020; Saheb et al., 2019). Similarly, many publications regarding Net Zero Energy Neighborhoods/Communities cite this concept as a possible pathway to alleviate energy poverty without focusing too much on the issue (Becchio et al., 2018; Gonzalez et al., 2012). As with Net Zero Energy Communities, PEDs might bring down energy prices due to increased self-production and the presence of prosumers. At the same time, reducing energy consumption in the first place will limit energy expenditure. Therefore, the main difference seems to be in the official endorsement of practices that could improve on inclusiveness, fairness and justice in the transition process. As explained by (Jenkins et al., 2016), this study also considers energy justice as divided in:

- Distributional Justice;
- Recognition-Based Justice; and
- Procedural Justice.

The first investigates where energy injustice emerges and how it is spatially distributed. The second investigates how and which sections of society are not adequately represented. The last explores how decision-makers have involved

local communities in the transition process. Renewable energy generation is delocalized by nature. Hence it can improve the distributional issue at least on a local level. The local generation of pollutants (e.g. NOx and PMs) can negatively affect those that live close to fossil fed power plants or highly trafficked areas. On the other hand, carbon emissions do not have an immediate effect locally and have the potential to affect the climate on a global scale. Hearn et al. (2021) developed a framework for an ex ante qualitative evaluation to implement during the PED design stage. The framework encompasses the three pillars of energy justice and expands upon them locally and globally. Zero Energy Communities only mention the importance of having a just community based on the Sanborn Principles of Sustainability but never expand on that. Carlisle et al. (2009) do not explain how to achieve a just community nor do they explain what the term implies.

4 | CONCLUSION

This paper aims to investigate the interconnections between PEDs and other similar concepts, provide a thorough analysis, improve clarity, avoid repetition, and homogenize terminology. This work carried out an analysis based on six main criteria of interest in the context of urban/district analysis: spatial resolution, energy balance, emissions, land use, energy efficiency, and energy justice.

The main and most obvious characteristic that makes PEDs stand out is their positive energy balance. In this sense, it is worth mentioning that its estimation is consistently affected by the three aforementioned typologies (Autonomous/Dynamic/Virtual). Although a district generating more energy than it needs has a higher appeal, which may facilitate its replication, further studies will be needed to evaluate it. Intense and immediate production of energy from PEDs can allow a district-wise positive balance, but also put further strain on the grid if not utilized immediately or stored. Battery storage and demand response, to name a few, need careful design and thought to allow proper utilization of the energy surplus and avoid curtailing and shedding. The annual character of the energy balance does not capture seasonalities. Thus, we propose a stricter balance resolution of 8 h to account for seasonal differences in energy generation and demand but also those throughout the day.

Both NZEC and PEDs consider energy efficiency at a building or district level. However, the approach needs to be also extended to the infrastructure, including its utilization, capacity and management. All concepts considered in this paper consider GHG emission as an important factor. They all tend to reach a near or completely zero-carbon balance.

However, although carbon emissions are incredibly important, other emission types seem to be missing in all the concepts investigated. PMs, Nitrogen Oxides and other forms of pollutants are known to cause damage and issues to the respiratory apparatus and therefore should be considered with more care. Other kinds of emissions should also be considered, such as gray emissions (embodied emissions) but also contaminants relative to extraction and production of raw material utilized to build PVs, batteries, and other materials utilized to produce RESs and increase energy efficiency. PEDs only contemplate land use from a social perspective and end-users perspective. NZEC have a more economical approach to the issue, considering the differences from an economic and technical perspective of utilizing brownfield or greenfield for renewable energy generation. Both approaches are valuable, and PEDs could include considerations regarding utilization and even reclaiming brownfields. Citizen participation is the key to PEDs. With a proper framework it is possible to include and work on all pillars of Energy Justice. Although also other concepts favor citizen participation, the current research on energy justice in PEDs seems to gain an edge.

From a technical standpoint, as of now, PEDs are defined as an urban area that produces more locally generated energy than required over 1 year span, aiming at net-zero carbon emissions. This goal is achieved by implementing a combination of highly energy-efficient buildings, renewable energy generation, and smart grid management interconnection. Moreover, energy justice plays a crucial role in making the transition possible and fair through citizen participation and targeted interventions.

To conclude, given the novelty and high appeal that PEDs currently have, the authors believe that this concept should include, as mentioned above, aspects that are now poorly investigated. In particular, more attention to land use and emissions beyond GHG emissions should be encouraged. Additionally, the higher attention PEDs give to the energy balance and energy justice is a crucial aspect that should be strengthened even more by linking them with a more specific and standardized economic framework and analysis. By doing this, it is then possible for PEDs to become a reference in the current urban scale energy transition, including all the different aspects considered by its predecessors.

AUTHOR CONTRIBUTIONS

Luca Casamassima: Conceptualization (lead); formal analysis (lead); investigation (equal); methodology (equal); validation (equal); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Luigi Bottecchia:** Conceptualization (supporting); formal analysis (supporting); investigation (equal); methodology (equal); validation (equal); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Axel Bruck:** Conceptualization (supporting); formal analysis (supporting); investigation (equal); methodology (equal); validation (equal); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Lukas Kranzl:** Methodology (supporting); supervision (supporting); validation (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Reinhard Haas:** Methodology (supporting); supervision (supporting); validation (supporting); writing – original draft (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTE

[1] The electricity grid or fuel supply system outside the physical district borders

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