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Report on PED Definitions, Characteristics and Key Performance Indicators

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2.1 Evolvement of the PED concept

Positive Energy Districts (PEDs) are recognised as one of the central pillars for driving the urban energy transition in Europe. The concept of PEDs can be traced back to the concept of net-zero energy districts (NZEDs) that corresponds to the transformation at the neighbourhood level triggered by the implementation of the EU 2020 energy and climate targets. The concept marked a shift from individual buildings to the neighbourhood level as a way to scale up the efforts and speed up the pace of the global energy transformation [1]. Building on NZED, the Energy Efficient Building Committee of the European Construction, Built Environment and Energy Efficient Building Technology Platform (ECTP) designed the concept of Positive Energy Blocks (PEB) to stimulate the citywide energy transition in Europe [1]. The concept was strongly promoted by the European Innovation Partnership on Smart Cities and Communities (EIP-SCC), which established an initiative on PEBs in 2016. The main goal of the initiative was to facilitate the deployment of 100 PEBs throughout EU and neighbouring countries by 2020 [2].

A step up from PEBs came the concept of Positive Energy Districts (PEDs). The European Commission (EC) endorsed the SET Plan Action 3.2 “Smart Cities and Communities” in June 2018. The main objective of Action 3.2 is to develop integrated and innovative solutions for the planning, deployment, and replication of PEDs. According to the Action, 100 PEDs are expected to be in concrete planning, construction or operation, synergistically connected to the energy system in Europe by 2025 [3].

The concept of PEBs/PEDs is fully recognised by the EC. Through pilot projects financed by the Horizon 2020, Horizon Europe and the Driving Urban Transitions Partnership (DUT) funding programmes, the EC supports a wide deployment of PEBs/PEDs. Since the implementation of the SET Plan Action 3.2, there has been a growing number of PED-oriented initiatives and projects at both the EU and national levels. However, there is not a common European definition of PEDs and as a result, different notions of PEDs are in use. Section 2 presents a review of PED definitions developed and used by a number of key initiatives and projects.

The Joint Programming Initiative Urban Europe (JPI UE) published a framework definition of PEDs in 2019. The framework seeks to create a joint vision on PEDs across Europe [3]. DUT has since updated the PED definition framework to make it more operable on the ground and the latest revision is known as “PED Definition Framework 3.0” (more information in Section 2). Despite being widely acknowledged by key stakeholders, there are still important questions concerning PED definitions that need to be further discussed in order to make the concept more workable and appealing to urban practitioners.

2.2 Existing PED-related Initiatives/projects and their PED definitions

2.2.1 PED Definitions Used by EU Organizations and Programmes

At the European level, there are several major organisations, initiatives or programmes, which have a stake in driving the deployment of PEDs. They are (i) the SET-Plan Action 3.2, (ii) the Horizon Framework Programmes, (iii) EC Joint Research Centre, (iv) JPI Urban Europe, (v) Driving Urban Transitions Partnership, (vi) European Energy Research Alliance (EERA), (vii) COST Action Positive Energy Districts European Network and (viii) International Energy Agency Annex 83 Positive Energy Districts. The PED definitions developed by them are widely adopted and are presented as follows.

SET-Plan Action 3.2. The SET-Plan defined PED as "a district with annual net zero energy import, and net zero CO_2 emissions working towards an annual local surplus production of renewable energy". They are expected to be implemented in newly built, retrofitted or mixed districts. According to the SET-Plan, PEDs should be driven by renewable energy and be an integral part of the urban and regional energy system. They should be based on high energy efficiency and make optimal use of technologies to reduce energy use and greenhouse gas (GHG) emissions. Besides the energy aspect, PEDs should offer affordable living for the inhabitants [3].

Horizon Framework Programmes. The concept of PEDs was first included in the Horizon 2020 proposal call for the Smart Cities and Communities lighthouse projects and in there, "Positive Energy Blocks/Districts consist of several buildings (new, retro- fitted or a combination of both) that actively manage their energy consumption and the energy flow between them and the wider energy system. Positive Energy Blocks/Districts have an annual positive energy balance. They make optimal use of elements such as advanced materials (e.g. bio-based materials), local RES, local storage, smart energy grids, demand-response, cutting edge energy management (electricity, heating and cooling), user interaction/involvement and information and communications technology (ICT). Positive Energy Blocks/Districts are designed to be integral part of the district/city energy system and have a positive impact on it (also from the circular economy point of view). Their design is intrinsically scalable, and they are well embedded in the spatial, economic, technical, environmental and social context of the project site" [4].The PED development was continuously supported by the subsequent Horizon Europe programme, in which the term "Positive Clean Energy Districts" was introduced and used alongside PEDs. The two terms are used interchangeably in the calls within the framework programme.

EC Joint Research Centre (JRC). PED is considered as an area with defined borders that has an overall positive energy balance over a year. It has buildings with a near zero or very low energy demand owing to their very high energy performance complying with applicable minimum energy performance requirements and local building codes. The building demand is covered to a very significant extent, or more, by renewable energy sources produced on-site or nearby. The primary purpose of a PED is to provide environmental, economic or social community benefits based on open and voluntary participation. A PED is autonomous and is effectively controlled by its citizens [5].

JPI Urban Europe (JPI UE). The reference framework definition for PEDs developed by JPI UE states that "Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero GHG emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environ- mental sustainability". Each PED is expected to find its own optimal balance between energy efficiency, energy flexibility and local/regional energy production on its way towards climate neutrality and energy surplus. While the resilience and security of energy supply are important guiding principles, the development of PEDs should also respect sustainability and inclusiveness and, in more general terms, enhance the quality of life [6].

ERA Joint Programme Smart Cities (EERA JPSC). According to EERA JPSC, PEDs are "mixed-use energy-efficient districts that have net zero CO2 emissions and actively manage an annual local surplus production of renewable energy. They require interaction and integration between buildings, the users and the regional energy, mobility and ICT system, while ensuring social, economic and environmental sustainability for current and future generations" [7].

Beyond the definition, different types and boundary definitions for PEDs were proposed. At the PED Definition Workshop organized by the EERA Joint Program Smart Cities and involved participants from +CityxChange partners as well as members from other projects and representatives from institutions, three different boundary approaches have been introduced [8].

- **Geographical boundary:** The spatial and physical limits of the PED, encompassing the district's buildings, sites, and infrastructure. These boundaries may be contiguous or composed of detached areas.
- **Functional boundary:** The energy grids that serve the PED, such as:
  - An electricity grid behind a substation functioning as an independent entity for the PED.
  - A district heating system that serves the PED, even if its service area extends beyond the district.
  - A gas network with similar functionality.
- **Virtual boundary:** Contractual limits of the PED, including energy production infrastructure owned by the district's occupants but located outside the geographical boundaries, such as an offshore wind turbine owned through shares by the PED community.

Addition to these boundaries, EERA introduced different PED types [7]. The purpose is to allow for system flexibility and better optimization of PEDs. The four PED types proposed are as follows:

- **PED-autonomous**: Net positive yearly energy balance within the geographical boundaries of the PED and internal energy balance at any moment in time (no imports from the hinterland) or even helping to balance the wider grid outside.
- **PED-dynamic**: Net positive yearly energy balance within the geographical boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages.
- **PED-virtual**: net positive yearly energy balance within the virtual boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages.

- **Pre-PED:** no net positive yearly energy balance within the geographical boundaries of the PED but energy difference acquired on the market by importing certified green energy (i.e. realizing a zero-carbon district).

These boundaries and types allow PEDs to be adapted to different urban contexts and energy infrastructures, offering a flexible approach to energy management at the district level while also distinguishing them.

Driving Urban Transitions Partnership (DUT). Building on the reference framework developed by JPI UE, the subsequent PED Reference Framework 2.0 published in 2019 as well as considering the challenges in operationalise the PED concept on the ground based on feedback from urban practitioners, DUT simplified the PED definition to make it more operable in practice. The DUT PED Definition Framework 3.0 states that "Positive Energy Districts (PEDs) are energy efficient and energy flexible urban neighborhoods or areas of connected buildings and facilities, that produce local renewable energy, achieve net zero greenhouse gas emissions, and actively contribute to overall climate neutrality. Core aspects are renewable energy production, affordability, and financial sustainability, enabling PEDs to unlock their full potential as drivers of systemic transformation. By integrating diverse systems and infrastructures such as energy, mobility, and ICT and fostering interactions between buildings, users, and regional networks, PEDs align with a clear mission toward sustainability. Through engagement at all levels of governance, the empowerment of local energy communities, and alignment of initiatives, PEDs secure energy supply and a good life for all in line with social, economic, and environmental sustainability" [9].

International Energy Agency (IEA) Annex 83. IEA Annex 83 adapted the PED definitions from SET-Plan Action 3.2 and EERA JPSC but with stronger emphasis on energy efficiency and the use of local renewable resources. It states that "Positive Energy Districts are energy-efficient districts with net zero greenhouse gas emissions and an annual positive energy balance. They prioritise the use of local renewable energy and resources. They seek to optimise the interaction and integration between buildings, the users, mobility, energy and ICT systems. Positive Energy Districts strive to bring positive impacts to the wider energy system as well as social, economic and environmental benefits to the communities. The assessment of the annual energy balance is open to any methods that are well defined and grounded on sound principles." [11].The IEA Annex 83 definition highlights especially the expectation of PEDs in bringing positive impacts to the wider energy system in addition to other social, economic, and environmental benefits, which is a crucial aspect that has arisen during the course of the PED transition in the last few years.

COST Action Positive Energy Districts European Network (PED-EU-NET). PED-EU-NET largely adopted the reference definition framework developed by JPI UE but with some modifications to make the concept more inclusive. The PED-EU-NET definition considers the requirement of an annual positive energy balance as optional provided that most of the other requirements in the JPI UE reference framework are respected. This definition is applied in the data collection of the PED Database (https://pedeu.net/map/) – an inventory jointly developed by PED-EU-NET, DUT and IEA Annex 83 that attempts to capture all existing PED cases across Europe [10].

2.2.2 PED Definitions used in Relevant Projects of National Programmes

There has been a booming of PED projects in recent years and each project interprets the concept of PEDs in its own way. As a result, there exists multitude of PED definitions. This section reviews the PED definitions used in fourteen prominent projects in the landscape of PEDs.

Project 'ATELIER'. ATELIER aims to create and replicate community-driven PEDs in two lighthouse cities (Amsterdam and Bilbao) and six fellow cities to save CO2 emissions and to demonstrate that integrated smart urban solutions support the deployment of PEDs. According to the project, PED is defined as a district that produces more renewable energy than it consumes on an annual basis. In addition to renewable energy production, the PED concept also considers energy efficiency and flexibility, energy autonomy and zero direct emissions of non-biogenicCO2. The PED demonstrations are composed of areas connected geographically as well as virtually through smart grids. The project developed a framework for the monitoring and evaluation of PEDs based on a set of Key Performance Indicators (KPIs) covering energy, environment, economy, electro-mobility, citizen engagement and governance. Besides, environmental impacts are evaluated from the life cycle perspective including the consumption of products and services within the PEDs [12].

Project '+CityxChange'.+CityxChange (Positive City Exchange) defines PEDs as urban areas composed of new and existing buildings, along with their surrounding neighborhoods, that generate local renewable energy while actively managing consumption and energy flows to the wider grid [13]. A PED maintains a positive annual energy balance, allowing the surplus to be shared with the surrounding city. This is achieved through increased energy efficiency, reduced demand, and the integration of local renewable city sources. The project aims to develop, deploy and scale up PEBs and PEDs in two lighthouse cities (Limerick and Trondheim) and five fellow cities to support the European Clean Energy Transition. The project not only focuses on the technical solutions around PEBs/PEDs but also the interaction between buildings, users, cities, the wider energy system, as well as the implications on city planning, digitalization, citizen involvement, regulations, socio-economic issues and so on. According to the project, PEB is defined as a compact area comprising at least three mixed use buildings (>15,000 m2), which produces more energy than it consumes over a year by including local renewable energy production and measures to reduce energy demand [13].

Project 'MAKING-CITY'. MAKING-CITY aims to develop new integrated strategies to address the low-carbon urban energy transformation through large-scale demonstrations in two lighthouse cities (Groningen and Oulu) and six fellow cities. The project seeks to establish evidence on using the PED concept as a foundation to progress towards sustainable urban transformation. The project defines PED as an urban area with clear boundaries comprising buildings of different typologies that actively manage the energy flow among them, as well as the larger energy system to reach an annual positive energy balance [14]. The PED concept used in the project includes positive energy buildings, on-site renewable energy systems, energy sharing, flexibility and optimization and smart control. The project developed guidelines for PED design, guidelines to calculate the annual primary energy balance and a GIS based methodology for identification of PED concept boundaries in cities.

Project 'POCITYF'. POCITYF aims to implement and demonstrate innovative solutions at the building and district level that enable the increase of energy self-consumption, energy savings and locally produced renewable energy. The project adopted the PED definition from the Horizon 2020 Framework Programme. The PED concept is achieved through measures such as building integrated photovoltaics, P2Penergy markets, storage solutions, integrated electro-mobility, integrated ICT solutions, active citizen engagement. The project facilitates the development of PEDs in mixed use urban districts with a focus on cultural heritage areas. Two lighthouse cities (Alkamar and Évora) serve as large-scale demonstrations of the proposed solutions and six fellow cities support the replication.

Project 'SPARCS'. SPARCS aims to create a network of sustainable energy positive and zero carbon communities in two lighthouse cities (Espoo and Leipzig) and five fellow cities. SPARCS largely adopted the PED definition framework developed by EERA JPSC with three types of PEDs, namely, PED-autonomous, PED-dynamic and PED-virtual. Both PED-autonomous and PED-dynamic have clearly defined geographical boundaries. PED-autonomous is completely self-sufficient with energy demand covered by onsite renewable sources. PED dynamic allows the import of external energy insofar as the annual energy balance is positive. PED-virtual operates within virtual boundaries, which allows the use of renewable energy sources or energy storage outside the geographical boundaries. However, renewable energy generation or energy storage that locate outside must be an asset of the district.

Project 'syn.ikia'. syn.ikia puts forth the concept of Sustainable Plus Energy Neighbourhood (SPEN) that strongly aligned with the broad concept of PEDs. SPEN is defined as a group of interconnected buildings with associated infrastructure, located within both a confined geographical area and a virtual boundary [15]. It aims to achieve more than 100% energy savings, 90% renewable energy generation triggered, 100%GHG emission reduction, and 10% life cycle costs reduction, compared to the level of2020 nearly zero-energy buildings (nZEBs). Additionally, a SPEN covers five main objectives including (i) net-zero GHG emissions, (ii) active management of energy surplus, (iii) cost efficiency and economic sustainability, (iv) improved indoor environment, and (v) social inclusiveness and affordable living. The project developed a methodological framework for the evaluation of SPEN including the assessment of the positive energy balance. syn.ikia aims to increase the share of SPENs with surplus renewable energy in different contexts, climates and markets in Europe.

Project 'Zukunfsquartier—Vienna'. The Project 'Zukunftsquartier' (translated as 'Future Neighbourhood') explores the feasibility of applying the plus energy neighbourhood concept in four project sites in Vienna. The project aims to develop a scientifically sound and practical definition that can be used to assess and certify PEDs as a cornerstone to support the national climate neutral target [16]. The PED concept focuses on 100% renewable energy supply. In addition to energy, economic feasibility and other sustainability requirements are considered. Based on the setup of system boundaries, the project proposes three types of PEDs:
•**PED Alpha**: a district that reaches a positive annual primary energy balance based on all energy services (operational energy and user electricity) and monthly conversion factors. A credit or discount based on structural density is applied.
•**A PED Beta:** meets the above criteria with the inclusion of private everyday mobility and a per capita RES credit for surpluses of the energy system by large RES power plants.
•**A PED Omega**: covers all the above energy services as well as the embodied energy for structure, building and mobility. On the basis of hourly conversion factors, the PED achieves a global warming potential below 500 kg/cap/annum. The definition can be extended to include emissions from individual consumption as a way to connect to individual carbon budgets.

Project 'PHVision—Heidelberg'. The City of Heidelberg in Germany envisions to transform the Patrick-Henry-Village into a PED with mixed living and working space for around 15,000 people [17]. The project defines PED as a district that produces more renewable energy than it consumes on an annual basis. The proposed PED is composed of a clearly defined geographical area and virtual system boundary that allows dynamic energy exchanges with the wider region. The project developed a method for calculating the energy balance including space heating, cooling, domestic hot water and electricity use in buildings as well as energy use in transportation. Concerning transportation, local public transport, private and business mobility are assumed to be entirely electric in the project and included in the energy balance calculation. In addition, the embodied energy related to the construction and renovation of buildings is considered. The project also devised a method for estimating the district's share in the total renewable energy potential of the region, which serves as a cap for potential green energy import.

ZEN Centre. The Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities is a Norwegian research centre. ZEN combines the concept of PEDs with climate neutrality. It aims to reduce its direct and indirect GHG emissions towards zero over its lifetime. The ZEN Centre developed a definition of ZENs and KPIs to assess them. A neighbourhood is defined as a group of interconnected buildings with associated infrastructure located within a confined geographical area. However, the system boundary for analysis of energy facilities serving the neighbourhood can include infrastructure for exchange, generation and storage of electricity and heat outside of the geographical boundary. The total GHG emissions are accounted based on a life-cycle assessment in all phases of the neighbourhood development including planning, implementation, operation and demolition. ZENs compensate the emissions through onsite renewable energy production during the operation phase and achieve a positive energy balance on a yearly basis. In addition to GHG emissions, other KPIs include energy, load, mobility, economy, spatial qualities and innovation. The definition and KPIs are tested in nine neighbourhood-scale demonstration sites in Norway [18, 19].

Project 'NEUTRALPATH'. NEUTRALPATH defines Positive and Clean Energy Districts (PCEDs) as urban areas made up of interconnected buildings that are both energy-efficient and flexible in their energy use. These districts are considered "clean" because they rely entirely on renewable energy sources and "positive" because they not only achieve net-zero greenhouse gas emissions but also generate a surplus of renewable energy. The project adapts both geographical and virtual boundaries in PCEDs. To realise PCEDs, the project implements a range of actions at both the building and district scales, including energy-efficient façade design, energy system optimisation, renewable energy integration, grid management, e-mobility, and community engagement. The proven solutions at the district level are expected to be scaled up at the city level. Istanbul, Ghent, and Vantaa as fellow cities are working alongside Lighthouse Cities Zaragoza and Dresden. The collaboration aims to integrate the PCED concept into local decarbonization strategies with a shared goal of achieving climate neutrality by 2050 [20].

Project 'ASCEND'. ASCEND considers Positive Clean Energy Districts (PCEDs) as comprising of five key pillars: active citizenship, zero-carbon frugal buildings, smart energy grids, decarbonized public spaces and mobility, and digital tools. At the core of this approach is an urban orchestrator, a public entity that coordinates all components and services to ensure long-term transformation at the district level. To facilitate collaboration and implementation, ASCEND connects each pillar to the urban orchestrator through a digital platform and a human network that engages local stakeholders in the transition to clean energy [21].

Project 'HARMONISE'. The HARMONISE project aims to transform traditional districts into PEDs. The project defines PEDs as urban areas with interconnected, energy-efficient buildings that achieve net-zero emissions and manage surplus renewable energy. It provides an interoperable, scalable solution for optimal PED design, management, and integration, using fog-enabled devices, blockchain-based transactive energy systems, and open-standard interfaces. By unifying energy transactions across electricity, heating, mobility, and storage networks, HARMONISE supports multi-sectoral PED expansion. The project will demonstrate its approach through four physical pilots and one digital pilot, integrating all components into a Supernova Grid to advance the European Super Grid transition [22].

Project 'PEDvolution'. PEDvolution envisions them as dynamic, evolving urban ecosystems that not only produce at least as much energy as they consume annually but also continuously adapt to changing external conditions. Rather than static endpoints, PEDs dynamically interact with urban development, legislation, renewable energy integration, electric mobility, and fluctuating energy markets. This perspective aligns with an evolutionary approach, where PEDs develop and optimize their structures in response to their surroundings. The project aims to facilitate the cross-sectoral integration and continuous evolution of PEDs through the development and implementation of seven interoperable solutions, focusing on social, technological, interoperability, and market aspects [23].

Project 'InterPED'. The InterPED project defines PEDs as interconnected urban areas that achieve net zero greenhouse gas emissions while actively managing renewable energy, storage, and waste heat to enhance efficiency and grid stability. InterPED's approach focuses on sector coupling, cross-vector integration, and demand flexibility, ensuring PEDs make optimal use of local renewable energy sources, storage, and excess/waste heat. A key component of the project is its scalable, cloud-based platform, which provides analytical, modeling, and optimization services for managing power, heating, cooling, and mobility systems within PEDs. Additionally, consumer engagement is central to InterPED's strategy, with participatory co-design processes enabling service providers and residents to collaborate on energy solutions. By fostering community-driven demand response strategies and ensuring system interoperability, InterPED aims to create replicable and commercially viable PED solutions, which will be tested in four large-scale pilot sites [24].

2.3 Comparison and discussion of existing PED definitions

Table 1 extracts a set of key elements in the PED concepts and compares them across the twenty-two programmes and projects under study. Based on the comparison, similarities and differences between the existing definitions are identified. All programmes and projects, except DUT and PED-EU-NET, consider a positive annual energy balance as a criterion. 14 (out of 18) include net zero GHG emissions as an additional target. This reflects the alignment of the PED concept with the EU's mission on climate-neutral and smart cities and enables PEDs one of the transition pathways towards climate-neutrality in the long-term. In terms of the scale of development, the terminology used varies from 'several buildings' and 'groups of connected buildings' to 'district' and 'neighbourhood'. While this versatility highlights the broad applicability of the PED concept, it makes it hard to compare PEDs across different projects as the complexity, challenges and level of achievement often depend on the scale of development. The existing programmes and projects also apply different approaches in the selection of PED boundaries. While some based on rigid geographical boundaries, others adopt a more flexible approach that allows the import of renewable energy outside the geographical boundaries of the district, an extension to the so called “virtual boundaries”. The introduction of “virtual boundaries” means that PEDs are not necessary energy autonomous. This significantly lowers the barrier to PED development (especially for districts where the availability of local renewable resources is limited) and as a result, makes the PED concept more inclusive. Regarding the means to achieve PEDs, the application of renewable energy supplies and energy efficiency measures are essential among all programmes and projects. Buildings are seen as a key component in the PED concept, although many projects also recognise the roles of energy storage, mobility, and ICT. Besides energy-related matters, almost all programmes and projects include social, economic, and environmental aspects in the PED concept. Different non-energy qualities are mentioned (e.g. inclusiveness, affordable living, citizen engagement, etc.) but their descriptions are rather general without concrete requirements.

Table 1: Comparison of key elements in the PED concepts across twenty-two relevant programmes and projects.

	Scale	Boundary	Types	Energy Balance	GHG emissions	Key Concepts				
						Energy	Mobility	Economy	ICT	Social
Horizon Programmes	Several Buildings	-	-	+	-	✓	--	--	✓	--
SET-Plan Action 3.2	District	-	-	+	Net Zero	✓	--	--	--	--
JPI Urban Europe	Groups of connected buildings	-	-	+	Net Zero	✓	✓	✓	✓	✓
JRC	--	Defined Boundaries	-	+	-	✓	--	--	--	--
EERA JPSC	District	Geographical, Functional and Virtual	PED-auto PED-dynamic PED-virtual pre-PED	+	Net Zero	✓	✓	✓	✓	✓
DUT	Urban areas	-	-	-	Net Zero	✓	✓	✓	✓	✓
PED-EU-NET	Groups of connected buildings	-	-	-	Net Zero	✓	✓	✓	✓	✓
IEA Annex 83	District	-	-	+	Net Zero	✓	✓	✓	✓	✓
ATELIER	District	Geographical and Virtual	-	+	Net Zero	✓	✓	✓	✓	✓
+CityxChange	District	Geographical, Functional and Virtual	PED-auto PED-dynamic PED-virtual pre-PED	+	Net Zero	✓	✓	✓	✓	✓
MAKING-CITY	District	Geographical, Functional and Virtual*	-	+	Decarbonization	✓	✓	✓	✓	✓
POCITYF	District	Geographical and Virtual	-	+	-	✓	✓	✓	✓	✓

	Scale	Boundary	Types	Energy Balance	GHG emissions	Key Concepts				
						Energy	Mobility	Economy	ICT	Social
SPARCS	District	Geographical and Virtual	-	+	Net Zero	✓	✓	✓	✓	✓
syn.ikia	Groups of connected buildings	Geographical, Functional and Virtual*	-	+	Net Zero	✓	✓	✓	✓	✓
Zukunfsquartier	District	-	PED-alpha PED-beta PED-omega	+	Net Zero	✓	✓	✓	✓	✓
PHVision	District	Geographical and Virtual	-	+	Net Zero	✓	✓	✓	✓	✓
ZEN	Neighbourho od	Geographical and Functional*	-	+	Net Zero	✓	✓	✓	--	✓
NEUTRALPATH	District	Geographical, Functional and Virtual*	-	+	Net Zero	✓	✓	✓	✓	✓
ASCEND	District	Geographical and Functional*	-	+	Net Zero	✓	✓	✓	✓	✓
Harmonise	District	-	-	+	Net Zero	✓	✓	--	✓	✓
PEDvolution	District	-	-	=/+	Net Zero**	✓	✓	--	✓	✓
InterPED	District	-	-	-	Net Zero	✓	✓	✓	✓	✓

* = not explicitly mentioned, authors' interpretation through documents and case study strategies
** = only mentioned in one of the case studies
-- = not considered or mentioned explicitly
- = information not available

2.4 Conclusion on main aspects in the framework of definition for PEDs

The concept of Positive Energy Districts has evolved from prior concepts of net-zero energy districts and positive energy blocks to become one of the key pillars underpinning Europe's urban energy transition. At the inception of the PED framework, there was a strong focus on the annual positive energy balance as a distinctive requirement. Earlier programmes and initiatives (including the SET-Plan Action 3.2, JPI UE, JRC and EERA JPSC) as well as the first wave of PED projects funded under Horizon 2020 (including +CityxChange, MAKING-CITY, SPARCS, POCITYF and ATELIER) emphasised on the production and active management of an annual energy surplus at the district level. However, the requirement of an annual positive energy balance sets a high barrier of entry to PEDs. Some practitioners criticise PEDs as an academic concept that is out of line with major urban priorities. Others criticise that the PED concept is exclusive as it is inaccessible for districts with limited opportunities for local renewable energy production. Over the last six years as the PED concept is being tested on the ground in different urban contexts, there has been a gradual shift in the narrative of PEDs. The annual positive energy balance is no longer considered a definitive criterion in some projects. The expectation of PEDs for bringing positive impacts to the districts/neighbourhoods as well as the wider energy system plays a more important role. The alignment of PEDs with the EU's climate-neutrality agenda and urban policies is another crucial element that has been strengthened in the recent PED development. Additionally, there has been more emphasis on the social, financial and governance considerations in the PED process, aspects such as community engagement, sustainable business models, participatory decision-making and so on were discussed in recent projects. The shift in the PED narrative, especially the meaning of "positive" from a narrow definition of a positive energy balance to a broader sense of driving positive urban changes makes the PED concept more inclusive, accessible, flexible and policy relevant. The drawback, however, lies on the vague distinction between PEDs and other existing urban development concepts such as climate-neutral districts or net-zero energy districts. Nevertheless, the outlook of PEDs is expected to go beyond the conceptual/definition refinement and towards more the practical strategies and approaches for operationalise the PED concept. Although the application of local renewable energy systems, energy efficiency measures, energy storage technologies and energy sharing/flexibility services are all key to the PED implementation, their practicality, performance, economic viability and social acceptance largely depend on the local contexts and boundary conditions. Learnings from existing PEDs (collected in the PED-EU-NET Database: https://pedeu.net/map/) will be an essential next step to support the replication of PEDs in different European cities.

3 PED Characteristics

3.1 District scales and building types

Positive Energy Districts (PEDs) vary widely in scale, type, and housing configurations, reflecting the diverse urban and regional contexts in which they are developed. These variations influence the implementation of energy solutions, infrastructure, and sustainability strategies.

While PEDs are primarily defined at the district level, the number of buildings within a district can range from a few to thousands, leading to variations in energy systems and management approaches. Some districts are small, with mainly residential buildings and localized renewable energy solutions, while others cover larger urban areas with mixed-use developments and more complex energy infrastructure. Large-scale districts require coordination among multiple stakeholders and advanced energy integration strategies.

3.1.1 District Types and Environments

PEDs exist in various district environments, each presenting unique challenges and opportunities for energy-positive development. These environments include:

- **Urban districts:** Typically, dense areas with a mix of residential, commercial, and public buildings, offering high potential for district heating, smart grid technologies, and integrated public transport systems.
- **Suburban districts:** More spread out with a balance of residential and commercial areas, often requiring decentralized energy solutions such as rooftop solar and energy storage.
- **Rural districts:** Characterized by lower population density, larger land availability for renewable energy installations, and opportunities for local energy independence.

Districts can also be classified based on their function and development stage:

- **Residential districts:** Primarily composed of housing, either single-family homes or apartment complexes.
- **Mixed-use districts:** Combining residential, commercial, and public buildings, enabling diversified energy demand and shared infrastructure.
- **Industrial and business districts:** Focused on commercial and manufacturing activities, often incorporating energy-efficient industrial processes and waste heat recovery.
- **New construction districts:** Areas built from the ground up with integrated energy efficiency measures and renewable energy systems.
- **Renovation and retrofitting districts:** Existing urban areas undergoing upgrades to improve energy performance and integrate modern energy solutions.
- **Transformation and re-use districts:** Older or underutilized areas being repurposed into energy-efficient zones.
- **Preservation districts:** Areas with historical or cultural significance where energy solutions must **be carefully integrated to maintain architectural integrity.**

3.1.2 Building Types in PEDs

The types of buildings in PEDs vary based on architectural and urban planning choices. Common housing configurations include:

- **Single-family homes:** Often found in suburban or rural PEDs, incorporating rooftop solar, heat pumps, and smart home technologies.
- **Multi-family apartment buildings:** Common in urban PEDs, featuring centralized or distributed renewable energy generation and shared energy management systems.

- **Passive houses and energy-efficient buildings:** Designed to minimize energy consumption through high-performance insulation, efficient ventilation, and optimized solar gain.
- **Retrofitted existing buildings:** Older structures upgraded with energy-efficient technologies and integrated into PED frameworks.

The scale, type, and environment of a district significantly influence its ability to become a Positive Energy District. Smaller districts with predominantly residential buildings may find it easier to implement localized renewable energy solutions, such as solar panels and battery storage. Meanwhile, larger mixed-use or industrial districts require more complex energy management strategies, including district heating, smart grids, and energy-sharing networks.

Urban districts benefit from high population density, making shared infrastructure more efficient, but they may face space limitations for renewable installations. Suburban and rural districts often have more space for renewable energy production but may struggle with lower energy demand density, requiring advanced storage or energy export solutions. Additionally, new developments can be planned with energy efficiency in mind, whereas retrofitting and renovation projects must balance modernization with existing structural constraints.

Overall, the diverse nature of PEDs means that energy-positive strategies must be flexible and adaptable to different scales, district types, and building configurations to maximize sustainability and energy efficiency.

3.2 Climate and technologies

The Positive Energy District frameworks and definitions published to date have provided the flexibility to select the most efficient and sustainable technologies as alternatives to fossil-fuel-based energy systems. The choice of technologies depends on many factors, such as whether the existing systems are centralized or decentralized, the climatic conditions, the existing energy infrastructure, and whether the district is urban, rural, or historic. Therefore, rather than a 'one size fits all' approach, several different technologies should be considered to ensure optimal performance for each district [25].

Looking at PED projects in general, it has been observed that district-wide centralized energy solutions are more common than building-wide decentralized solutions [25]. This is mainly because larger units operate more efficiently and are easier to manage. Additionally, district heating was the most common technology used, followed by heat pumps and PV technologies. It is important to point out that in some studies district heating was counted as part of the multi energy carriers, while others would consider it as an external energy network [26]. It was also found that many districts use a mix of technologies such as solar and district heating, or geothermal and wind energy. Reasons for this would include factors such as suitable land, climatic conditions and existing energy infrastructure [27].

PV systems were the most widely utilized renewable energy technology across these projects [27]. The main reasons for the popularity of PV systems in many countries can be related to decreasing costs, the simplicity of installation specially in urban areas where space is an issue and the increase in the number of companies offering this technology. Although solar energy is the most preferred technology even in the colder climates, the solar energy generation mismatch influences the PED types. For example, in cold climates, solar energy generation is not enough specially in winter months where the sunlight is scarce. In order to fulfill the remaining energy demand, districts in the colder climates tend to adopt the virtual PED Concept. Additionally, heat pumps are also widely used, especially in northern European countries where the infrastructure for heat production and distribution is well developed. In southern Europe, on the other hand, district heating systems are less developed because of the low heating demand caused by these countries' geographical and climatic location. This difference clearly illustrates the impact of climate types on the choice of technology [25].

Although wind energy is one of the most effective renewable energy sources, it is one of the least preferred technologies. The main reasons for this are lack of space in urban areas and the cost of installment. Although wind energy is a technology that can meet the high energy demand in urban areas, it seems difficult to implement unless the concept of virtual boundaries is adopted.

In conclusion, the choice of technology for PEDs varies depending on geographical, climatic, and infrastructural conditions. In many regions, solar energy and district heating are at the forefront, while other technologies such as wind energy play a supporting role. Especially in cold climates, where solar energy production is insufficient, the flexibility to adopt virtual solutions is of significant importance to select appropriate technologies for regional needs and to achieve a sustainable energy transition. The selection of technologies in PEDs should be context-specific, taking into account that the geographical and climatic variations that significantly affect these choices. To create successful PEDs, it is essential to consider the unique characteristics of each district, including its climate, infrastructure, and urban or rural setting. The ability to integrate a wide range of technologies allows PEDs to effectively transition to carbon neutrality while addressing the diverse challenges and opportunities of different environment.

4 PED Assessment Methods

4.1 Review of assessment methods in existing PED projects

Assessment methods for PEDs vary across projects, as no standardized methodology has been established. In general, these methods differ in two key aspects: (1) energy balance assessment, which determines whether a district qualifies as a PED, and (2) key performance indicators (KPIs), which evaluate various aspects of a district's progress. This section provides a general overview of these assessment methods, highlighting how different projects have adapted them based on their specific priorities and objectives.

4.1.1 Energy Balance Calculation

MAKING-CITY (MC)

The MAKING-CITY project has developed a structured methodology to calculate the annual primary energy balance (PEB) of Positive Energy Districts (PEDs) [28]. A district qualifies as a PED if it achieves a negative annual PEB, meaning it exports more primary energy than it imports within its defined boundaries, which can be geographic, functional, or virtual.

The calculation process begins with determining the PED boundary, followed by calculating energy needs and energy use within the district. Next, the methodology assesses on-site renewable energy generation and determines the amount of delivered energy required to meet the district's demand. These values are then converted into primary energy, allowing for the calculation of the energy balance. Finally, all energy flows within the district are visualized in a Sankey diagram, providing a clear representation of the PED's energy performance [28].

To determine the annual PEB, both delivered and exported energy are converted into primary energy using country-specific primary energy factors (PEFs). These factors account for the energy consumed throughout the supply chain, distinguishing between renewable and non-renewable sources, with the non-renewable share used in this assessment. The final step visualizes all energy flows within the district, ensuring a comprehensive evaluation of the PED's energy performance.

Zukunftsquartier Wien (future district Vienna, ZQW)

The ZQW project by UIV Urban Innovation Vienna, similar to the MAKING-CITY project, relies on the calculation of a PEB [16, 29]. The PEB is determined by subtracting the total primary energy imported from the total primary energy exported, with an additional proportional allocation of the renewable electrical energy potential of the country and a mobility compensation term. The assessment boundary aligns with the physical district boundary.

To illustrate using the type "PED Beta" in the project as an example, for a district to be classified as a PED, the PEB must exceed a calculated PEB target value, which scales with the Floor Area Ratio (FAR)—the ratio of the gross floor area (TGFA) to the site coverage area of a building. This adjustable PEB target value is described as the Density Factor, derived using simplified assumptions and results from PV simulations of real Austrian districts with varying site densities.

The annual PEB is determined by calculating the total primary energy exported (TPE) minus the total primary energy imported (TPI) per area within the assessment boundary. Primary energy is derived from final energy use and primary energy factors. In the energy balance, electricity imported from wind power peak shaving (curtailed wind energy) is considered primary energy-neutral, a concept known as Regional Renewable Peak Shaving.

To enhance the regional balance of renewable energy sources, the EE-Credit represents a population-proportional allocation of the country's renewable electrical energy potential to the district. Energy from large-scale renewable power plants—such as wind farms, hydroelectric plants, and biomass-fuelled combined heat and power plants—is first assigned to large consumers and energy uses that cannot be met locally. The remaining energy is then distributed among Austrian residents, and the cumulative EE-Credit of all building residents positively impacts the PEB. When mobility energy demand is included, the total district energy demand increases. To account for this additional requirement, a predefined term, Mobility Plus, is added to the energy balance, positively influencing the PEB.

4.1.2 Key Performance Indicators

Key Performance Indicators have emerged as one of the primary tools for assessing the diverse aspects of PEDs. Given the complexity and multifaceted nature of PEDs—ranging from energy efficiency and renewable energy integration to social and economic sustainability— KPIs provide a structured and measurable approach to evaluation. They allow for the clear tracking of progress and identification of areas requiring improvement.

ZEN. The Norwegian ZEN Research Centre's ZEN and syn.ikia's concepts share a foundational goal: achieving near-zero energy consumption while maximizing the utilization of renewable energy sources. ZEN emphasizes the integration of interconnected buildings within a defined geographical area with careful planning and design to minimize life cycle emissions. ZEN employs 42 key performance indicators across six primary categories—Greenhouse Gas Emissions, Energy, Power, Urban Form and Land Use, Mobility, and Economy—ensuring comprehensive assessment within defined system boundaries [19].

syn.ikia [15] evaluates the districts (SPENs) through 44 KPIs across five categories: energy and environmental performance, economic factors, indoor environmental quality, social indicators, and smartness and energy flexibility. This multifaceted approach aims to address the energy trilemma of security, equity, and sustainability while promoting social inclusivity and economic sustainability.

MAKING-CITY [30] exemplifies the practical application of Positive Energy Districts, aiming to establish neighbourhoods that achieve net-zero energy import and surplus renewable energy production. The project integrates a multi-faceted approach that addresses technical, social, and regulatory challenges. Utilizing 20 key performance indicators across categories such as energy and environment, mobility, governance, and citizen engagement. One of the features that makes MAKING-CITY different than others, is the project's PED-readiness indicator tool. This tool helps municipalities evaluate how ready they are to implement Positive Energy Districts. It offers pre-evaluation indicators for over 6,000 cities across Europe, along with self-evaluation questions that prompt local authorities to consider their current capabilities.

+CityxChange [31] aims to develop sustainable urban solutions by creating Positive Energy Blocks (PEBs) that scale up to Positive Energy Districts, ultimately contributing to climate-neutral cities. It focuses on innovative energy strategies such as energy reduction, efficiency measures, local renewable energy generation, energy storage, flexibility in energy use, and peer-to-peer energy trading. The project employs 33 Key Performance Indicators across three categories: Integrated Planning and Design, Common Energy Market, and Community Xchange. A distinguishing feature of the +CityxChange project is the assignment of expected targets for each KPI. This approach allows for specific accountability, setting +CityxChange apart from other initiatives in the field.

POCITYF [32] focuses on mixed-use urban areas with cultural heritage, aims to create sustainable and inclusive urban environments by integrating PEBs with grid flexibility, e-mobility solutions, innovative ICT technologies, and citizen engagement strategies, all while preserving urban cultural heritage. The project demonstrates solutions at both building and district levels to increase energy self-consumption, enhance energy savings, and integrate locally produced renewable energy. Key strategies are comparable to those in the +CityxChange project, including energy management, energy storage solutions to support grid flexibility, and the reduction of energy curtailment. Active citizen engagement and co-creation processes are also very important for the project, ensuring that residents are at the centre of decision-making, planning, and problem-solving. To monitor and evaluate progress, POCITYF established 63 Key Performance Indicators, refined from an initial list of 258 potential indicators sourced from the Smart Cities Information System (SCIS), CITYkeys, and other projects focusing on Positive Energy District evaluation. These KPIs are categorized into eight dimensions: energy, environmental, economic, ICT, mobility, social, governance, and propagation.

ATELIER's [12] KPI framework consists of 86 KPIs grouped into seven categories: energy, environmental, economic, mobility, citizen engagement, upscaling and replication, and knowledge sharing. These categories comprehensively address the technical, environmental, economic and social aspects of Positive Energy Districts. The KPIs are designed to ensure scalability and replication across different contexts while advancing knowledge sharing and policy development to support the energy transition.

PEDvolution [33] employs a unique assessment method that integrates KPIs within various business use cases to ensure a comprehensive evaluation PEDs. The framework consists of 10 distinct business use cases, under which a total of 55 KPIs are distributed. Since many KPIs are relevant to multiple aspects of PED development, some are repeated across different use cases. The assessment method focuses on several key areas including: (1) enhancing market value and financial viability through certification and sustainability verification, (2) optimizing energy efficiency and cost-effectiveness by improving building stock and leveraging energy communities, and (3) advancing grid and energy system operations by utilizing flexibility and sub-balancing areas. Additionally, the framework emphasizes reducing dependency on fossil fuels for district heating and cooling, reinforcing PEDs as a crucial component of the energy transition.

4.2 Test of selected PED assessment methods

A recent study by Fraunhofer [34] systematically analysed the assessment methods from three projects: MAKING-CITY, Zukunftsquartier Wien (ZQW), and ZEN. These three assessment methods were chosen because they differ substantially from each other and together, they capture a wide variety of possible calculation approaches. They range from simple calculation schemes (MAKING-CITY) to well elaborated calculations considering different urban context factors (ZQW) and assessment using sub-annual data instead of a single annual energy balance (ZEN). The three methodologies were tested using the same set of case studies, the results were compared in terms of the general practicality of the methodologies as well as their fulfilment of the PED objectives. The following section presents a summary of the findings and conclusions derived from this study.

MAKING-CITY (MC) Methodology

The MC methodology is straightforward, quick to apply, and easily transferable to different districts. It is seen as coherent and comprehensive, with the use of Sankey diagrams enhancing the understanding of energy flows within districts. One of the strengths of this methodology is its virtual boundary that allows wind power to be counted as on-site generation, facilitating energy sharing beyond physical district boundaries. However, this virtual boundary can lead to issues as energy flows that influence the energy balance can be selectively included, and vice versa. The inclusion of mobility energy demands is another concern, as it is not mandatory within the MC methodology but should be considered in the PED framework due to its significant role in energy consumption. Additionally, the use of Primary Energy Factors (PEFs) has been noted as a challenge, as the values and calculation methods for PEFs vary significantly across EU member states, leading to discrepancies in energy assessments. Despite these challenges, the MC methodology's ability to capture energy sharing and its application of centralized optimization have consistently yielded better results in case studies, highlighting its potential in promoting PEDs.

Zukunftsquartier Wien (ZQW) Methodology

The ZQW methodology aims to capture multiple urban development aspects in a single equation and as a result, the method is more complex and labour-intensive than MC. Its Density Factor, which plays a central role in the methodology, depends heavily on local data availability, making it challenging to adapt and transfer across different cities/countries. While the scaling with the Floor Area Ratio (FAR) compensates higher density development to facilitate PEDs in urban areas, it risks compromising quality of life, which is also a core principle of PEDs. The use of Energy Efficiency Credits (EE-Credit) also presents limitations, as commercial districts with lower populations may be disadvantaged due to higher energy demands. The methodology's inclusion of Mobility Plus, which compensates for additional mobility-related energy demands, is an advantage, though it remains unclear how it should be applied when only a subset of mobility options is considered. Furthermore, the approach towards regional renewable energy imports is problematic, as these imports may not always align with the district's renewable energy needs, and the Regional Renewable Peak Shaving concept raises questions about its feasibility. Like MC, ZQW also faces issues with the use of PEFs, as wind energy imports are not clearly treated as on-site generation, diminishing their potential to incentivize Power Purchase Agreements (PPAs).

Zero Emission Neighbourhood (ZEN) Methodology

The ZEN methodology is noted for its coherence and thorough documentation, although its application requires higher level of expertise due to the use of hourly data and the generation of predefined plots. The methodology's reliance on reference projects tailored to each district ensures broad applicability, but its focus on multiple KPIs rather than a single overall indicator makes the results difficult to interpret and compare. Extreme values, such as a peak load resulting from a single moment of high electricity import, can significantly affect some KPIs, complicating the evaluation of energy systems. Despite this, ZEN's use of multiple KPIs helps identify potential design issues within energy systems and provides valuable insights. However, the methodology's reliance on final energy imports and exports without differentiating between energy carriers and their environmental impacts is a limitation. For example, grid electricity and biomass are treated equally, despite having different greenhouse gas emissions. Additionally, ZEN does not use PEFs, which complicates the comparison of energy sources and reduces the incentive for districts to enter into PPAs for renewable energy supply. The disconnection between wind energy imports and on-site generation further diminishes the potential for green electricity imports that might help to reduce the carbon intensity of the district's energy mix.

Summary

Each assessment methodology has its own advantages and challenges and there is clearly a trade-off between simplicity and integrity of the assessment methods. MC appears to be universal and simple to apply but does not adequately consider enough contextual factors to capture the PED concept completely. Conversely, ZQW combines multiple contextual factors in a single final equation but can increase the complexity level and make the assessment methodology difficult to apply and hardly adaptable. ZEN utilises a unique approach in comparison to the other assessment methods by comparing a range of KPIs on hourly data against a reference project. However, the results can often be difficult to comprehend and the calculation of multiple KPIs can complicate the application.

In summary, the findings of the study pointed out that: (1) the objective of the assessment should not be solely on limiting the energy import and maximising the export of the district. A PED should be seen as a district that delivers positive impacts to the wider area by optimally utilising its own boundary conditions. Therefore, the assessment should also examine the energy exchanges between the PED and the surrounding energy systems to ensure conducive energy flows and prevent undesirable surplus generation; (2) relying solely on annual calculations (that is common for many PED project) is insufficient to assess the interaction between the district and the wider energy systems. Some energy-related performance indicators are best considered at least partly at an hourly level. Finally, the findings suggest that a positive energy balance might not be considered as a prerequisite of PEDs as this strict requirement sets a high entry barrier for districts that lack the intrinsic factors for surplus renewable energy production. For PED as an inclusive framework, the focus should be on delivering positive impacts for the districts and the wider energy systems; whilst the positive energy balance can be seen as a complementary rather than a mandatory condition.

4.3 Conclusion with recommendation on PED assessment methods and a PED framework

This section provides an overview of the PED framework and assessment methods, highlighting their current limitations and challenges. It examines key aspects such as the definition of PED boundaries, the applicability across different settlement types and the evaluation of energy balance within these districts. By analysing these shortcomings, this section aims to identify gaps in current PED assessment approaches and propose recommendations for improvement. The discussion will focus on refining PED boundaries, enhancing assessment methods to accommodate different district characteristics, and improving the evaluation of energy balance and flexibility. Addressing these issues is essential to developing a more standardized yet adaptable framework that can effectively guide PED implementation across various urban and regional settings.

4.3.1 Scales and Boundaries

The definition of a district, as outlined by the Cambridge Dictionary, refers to a designated area within a country or city, typically larger than a block or neighbourhood [35]. However, this definition remains flexible, leading to ambiguity in defining Positive Energy Districts. Terms like “urban areas,” “blocks,” and “neighbourhoods” are often used [36], but they lack clear spatial criteria. While districts are generally considered larger areas, data from the PED EU Net database [10] shows that most PED projects involve fewer than 100 buildings, suggesting that a PED’s size should not be strictly defined as long as it meets PED principles. However, energy demands, and renewable energy potential differ significantly between rural and urban areas, making it challenging for all districts to meet their needs within their physical boundaries. The JPI Urban PED definition provides flexibility by allowing both local and regional energy production, helping address energy surpluses and system complexity [6].The concept of Virtual-PEDs remains controversial, as it could prioritize energy balance over actual emissions reductions [28], yet tailored solutions remain essential for achieving climate neutrality.

Another major challenge is mobility-related energy, which extends beyond district boundaries, involving commuters, visitors, and residents. While PEDs can generate their own energy, mobility remains inconsistently integrated due to the lack of standardized performance criteria. Regional variations in emission accounting models further complicate assessments [37]. Despite its role in CO_2 reduction and energy storage, mobility is often excluded from PED frameworks, limiting their ability to address transportation energy demands [35].

4.3.2 Settlement Types

The success of PEDs depends on local factors such as renewable energy availability, infrastructure, population density, and energy consumption patterns. These variables shape PED design and implementation, requiring tailored solutions for different districts. However, the PED concept does not distinguish between urban, rural, or historic contexts, applying the same requirements to all, despite studies showing that densely populated urban areas with cultural heritage values face significant technical and regulatory challenges [37]. Urban districts often lack space for on-site renewable energy generation, making it difficult to match energy demand with local production [38]. In contrast, rural areas typically have more land and greater flexibility for deploying renewables, making PED implementation easier. Additionally, newly developing districts have a higher potential for PED success than historic areas, where retrofitting faces technical and aesthetic barriers [39].

Given these challenges, energy exchange beyond district boundaries can improve urban PED feasibility. Producing energy externally can be more efficient and cost-effective, which points to the use of virtual boundaries to access external resources [25, 37]. When space is limited, Power Purchase Agreements (PPAs) or Green Energy Certificates offer alternative pathways to climate neutrality, as recognized by Article 19 of the Renewable Energy Directive 2018/2001/EU. While this deviates from the traditional PED model of local production, virtual boundaries provide urban areas an opportunity to achieve PED goals despite the spatial constraints.

4.3.3 Energy Balance Calculation

A positive energy balance is a core principle of PEDs often serving as the primary metric for PED qualification. However, energy balance calculations are complex and the lack of a harmonized methodology across Member States further complicates assessment, as primary energy balance calculations vary widely.

PEFs, which reflect energy conversion and distribution efficiency, differ by country, making international comparisons difficult. Some nations assign a PEF of zero for renewables, while others do not, creating inconsistencies [28]. Additionally, as the energy system transitions to renewables, primary energy consumption becomes a less relevant indicator, as reductions in primary energy do not always equate to lower final energy use [40].

A recent study highlights that focusing solely on energy balance overlooks efficiency which explains why districts with high generation potential may still have inefficient systems [34]. Moreover, strict energy balance criteria often exclude many districts from achieving PED status, suggesting that assessment methods should offer flexible pathways to encourage progress toward PED goals. While energy balance is important, it should not be the sole determinant of PED status. Assessments must consider efficiency, system improvements, and climate-neutral strategies, ensuring that all districts—regardless of initial conditions—are recognised in their transition toward sustainability.

4.3.4 Assessment Methods

A number of assessment frameworks have been devised for the evaluation of PEDs, each incorporating distinct methodologies and key performance indicators. However, a review of several European PED projects reveals significant inconsistencies and challenges in the existing methods. The assessment frameworks differ in their approaches to defining PED boundaries, applying KPIs, and ensuring comparability across different settlement types, such as urban and rural areas or regions with varying climatic conditions. Data accessibility also remains a major concern, as some methods rely on high-resolution hourly data, which many districts lack the necessary technologies to collect. Furthermore, differences in how KPIs are calculated—such as whether they rely on primary or final energy—complicate the standardization of assessments, leading to inconsistencies in the evaluation.

Renewable energy, efficiency, and flexibility emerge as the most assessed aspects within PED frameworks, yet each presents unique shortcomings. Renewable energy assessments struggle with geographic disparities, where regions with lower solar or wind resources face difficulties in achieving high renewable energy shares. Similarly, densely populated urban areas have limited space for on-site renewable energy generation, making direct comparisons with rural PEDs problematic. Energy efficiency evaluations also vary significantly, with some relying on historical demand data, which may not account for emerging electrification trends like heat pumps and electric vehicles. Flexibility assessments, often based on peak load reduction, may fail to capture the broader adaptability of energy systems, particularly as electrification increases. Given these challenges, there is a clear need for more standardized yet adaptable PED assessment methods that ensure fairness, accuracy, and applicability across diverse district types.

4.3.5 Summary

Given these considerations, assessment methods should be streamlined to ensure consistency across the EU while accounting for the varying limitations of different countries. Not all districts have access to advanced data or measurement technologies, so assessment methods must be flexible and considerate of these challenges. Additionally, the methods should focus on the most critical aspects of PEDs, including renewable energy potential, energy efficiency, and mobility integration, ensuring that districts are assessed on a fair and equitable basis.

In conclusion, this study reviewed the definitions and assessment frameworks of a number of existing PED projects. It is found that, in order to bolster the uptake of PEDs, a PED framework that aligns with the EU's climate neutrality agenda and other urban priorities is key. At the same time, by considering local challenges and promoting a more flexible assessment process, the PED concept will become more inclusive and relevant to local development. This will help to mobilise support of local stakeholders in PED developments and warrant PEDs a pathway towards positive urban changes.

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6 PED Key Performance Indicators

Chapter 2 introduces several PED concepts and definitions with varying levels of differences. The different analysed prominent EU programmes and PED-relevant projects also show a wide range of KPIs covering the three pillars - environmental, economic, and social - of sustainability. As PED relevant KPIs are not yet consolidated either and cover a diverse field of sustainability aspects, it is important to establish a common ground for performance assessment.
The aim of the next chapters is to define a common core indicator set for PEDs by assessing the commonalities in existing PED definitions.

6.1 Methodology of core PED KPI assessment

To establish a standardized set of PED indicators, various PED definitions were first gathered from literature, focusing on key EU programmes and PED-related projects across Europe. Based on Albert-Seifried et al. (2022) 4 initiatives that outline EU-level decarbonisation objectives and research areas for Positive Energy Districts and 6 lighthouse projects, each offering its own interpretation of PEDs are analysed:

- the SET-Plan Action 3.2
- Horizon 2020 Framework Programme – Smart Cities and Communities calls
- JPI UE
- the European Energy Research Alliance
- ATELIER
- MAKING-CITY
- POCITYF
- SPARCS
- +CityxChange
- syn.ikia

All of these sources were first evaluated based on whether they provided developed KPI sets (none of the EU initiatives defined KPIs, whereas all H2020 projects did). These KPI sets were then compiled alongside additional literature sources to create a comprehensive pool of indicators relevant to this field.

Figure 1: Methodology of core KPI development

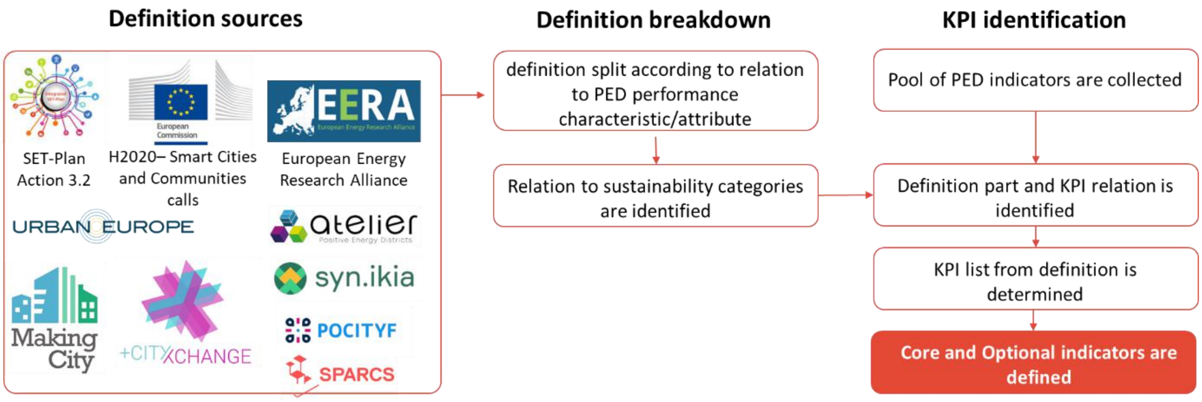

Figure *1* shows the methodology steps towards identifying the core PED indicators. The main principle of the methodology is that by analysing the PED definitions, the KPIs covering the stated PED objectives can be defined. To identify commonalities based on the breakdown of PED definitions, the following steps were followed:

1. The definitions were deconstructed by segmenting the text according to the PED performance characteristic or attribute each sentence pertained to.
2. The primary sustainability categories and subcategories corresponding to each section of a definition were determined.
3. Relevant KPIs capable of measuring PED performance for each identified category and subcategory were selected from the compiled indicator pool.
4. The findings from definition deconstruction and KPI assignment were compared, leading to the determination of a cutoff point between Core and Optional indicators to define the most prevalent PED themes and KPIs.

Figure 2: Example definition breakdown

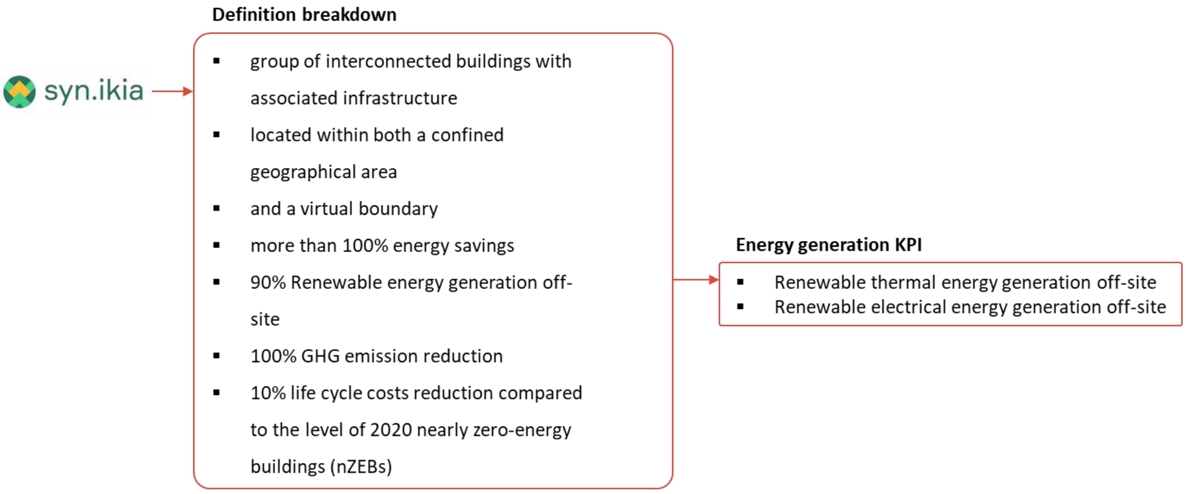

Figure *2* shows an example for applying the methodology to the syn.ikia definition. Step 1 results in seven distinct statements, one of which states: "90% Renewable energy generation off-site." This statement (Step 2) falls under the Energy topic, specifically within the Energy Generation subtopic. From the indicator pool, KPIs measuring renewable or non-renewable thermal or electrical energy generation on- or off-site (Step 3) can be identified to evaluate compliance with this definition. In comparison to other indicators, energy generation KPIs are considered Core indicators in PED developments (Step 4).

6.2 Results of the core PED KPI assessment

Step 2 of the assessment of the PED definitions showed that the different PED definition can be related to indicators in the following categories: Energy, Environmental Performance, Economic performance, Society and Residents, Mobility, Materials and Resources and Governance (Table 1).

Table 1: KPI Categories and Subcategories considered in at least one of the PED definitions

Main category	Subcategory
Energy	Energy generation
	Usage factors
	Energy balance

	Energy efficiency
	Energy savings
	Active management
	Flexibility
Environmental Performance	Emission
	Emission reduction
	Resilience
Economic performance	Cost
	Cost reduction
Society and Residents	Participatory approach
	Life quality of users
	Inclusiveness
	Affordability
Mobility	Mobility
Materials and Resources	Materials
Governance	Scalability
	Local context

The Energy category is represented in all the investigated definitions with clear performance targets. The results also show that the energy KPIs cover the three most important functions of districts in the context of their urban energy system: energy production energy efficiency and energy flexibility topics. However, the other sustainability categories are not well covered in the different categories, except the

The assessment of PED definitions reveals that only the aspects of Energy Generation, Energy Balance, Energy Efficiency, and Active Management were included in at least 7 out of the 11 definitions. Additionally, five definitions also take into account GHG Emissions and Energy Flexibility, while four incorporate Participatory Approaches. All other PED aspects appear in only one definition. Based on these findings, the cutoff point for Core indicators is set at a minimum of four mentions. Table presents the Core categories along with the corresponding KPIs that can be used to measure PED performance concerning these requirements.

The common indicator set (Table 2) primarily consists of energy-related KPIs, with GHG emissions being the only widely considered non-energy sustainability indicator. This indicates that, at present, the common indicator set addresses the Environmental dimension of sustainability, while the Social and Economic dimensions remain mostly overlooked.

Beyond the common indicators, additional, less frequently mentioned KPIs were identified, covering other aspects of sustainability. These include environmental factors (Resilience, Mobility, Materials and Resources, Local Context), economic aspects (Cost Reduction, Scalability), and social dimensions (Quality of Life for Users, Inclusiveness, Affordability). These indicators are categorized as optional, meaning their application may depend on the specific ambitions of individual PED developments.

The definitions also establish district characteristics, focusing on geographical boundaries (typically defined as districts with multiple interconnected buildings), usage type (mixed-use), building type (new developments or renovations), and included components (buildings and energy systems). While these characteristics are quantifiable, they differ from performance indicators as they do not measure PED district performance directly. However, they are essential for defining the PED concept, helping determine the types of districts that can pursue PED ambitions and apply the developed methodologies.

Table 2: Core PED KPIs

Category	Identified core KPI
Energy generation	Renewable thermal energy generation off-site
	Renewable electrical energy generation off-site
	Non-renewable thermal energy generation off-site
	Non-renewable electric energy generation off-site
	Renewable thermal energy generation on-site
	Renewable electrical energy generation on-site
	Non-renewable thermal energy generation on-site
	Non-renewable electric energy generation on-site Ratio of generated renewable energy used within the PED boundaries
Energy balance	Energy imported from outside the PED
	Energy exported from the PED
	Renewable energy imported from outside PED
	Renewable energy exported from the PED
Energy efficiency	Total primary energy demand
	Total annual saved primary energy
Active management	Integrated Building Management Systems Percentage of systems with smart energy meters, Percentage of peak load reduction
Flexibility	Flexibility index Energy storage capacity installed
GHG emissions	CO2 emission
	non-CO2 GHG emission
	GHG emission
	CO2 emission reduction
	non-CO2 GHG emission reduction
	GHG emission reduction
Participatory approaches	Local community involvement in the implementation and planning phase Energy citizenship

6.3 References

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