Let's make PED work

How current knowledge can contribute to future positive energy districts

Nikolic, Jelena; Thellufsen, Jakob Zinck; Sorknæs, Peter; Madsen, Poul Thøis; Nørgaard, Lasse Schytt

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Let's make PED work - How current knowledge can contribute to future positive energy districts

Jelena Nikolic *, Jakob Zinck Thellufsen, Peter Sorknæs, Poul Thøis Madsen, Lasse Schytt Nørgaard

Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark

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ABSTRACT

The concept of Positive Energy Districts (PEDs) i.e. urban units that produce surplus energy, has been recognized as a possible enabler of energy change. In literature, PEDs are defined in three main ways: virtual, dynamic, and autonomous, each offering different system boundaries for energy production. This paper examines these definitions while varying the inclusion of energy sectors (industry, transportation, buildings), enabling an assessment of PEDs as a tool to quantify the impact of district size and sectoral coverage. The general methodology presented in the study has been applied to district of Aalborg East in Denmark, to demonstrate its practical utility. Results indicate that system complexity significantly affects PED feasibility, influenced by local conditions such as weather and land availability. The choice of PED definition determines which energy sectors can be feasibly included. In this case, when energy-intensive sectors like industry and transportation are considered, the most feasible PED is achieved through the virtual approach. Compared to PEDs in which energy is strictly produced within the system boundaries, the annual costs of the PED virtual are 6 % lower than those of the PED dynamic model. Furthermore, even when the PED includes only households, the amount of energy produced but not utilized within the PED in the virtual model is 77 % lower compared to the autonomous model, and 20 % lower compared to the dynamic model.

Finally, the study highlights the importance of tailoring PED strategies to local contexts and integrating them into broader urban energy networks. This ensures electricity exchange between districts, supports national decarbonization goals, and promotes social inclusion and climate neutrality.

1. Introduction

As 75 % of the world's total final energy is used in urban areas, they should represent the carriers of energy changes (International Energy Agency, 2020). The importance of cities in the process of energy transition is evidenced by the 11th Sustainable Development Goal (Sustainable cities and communities), which emphasizes that cities and communities should be inclusive, safe, resilient, and sustainable (United Nations, 2025). In this regard, cities have become the subject of new policies at different levels. The European Union (EU) has adopted the Integrated Strategic Energy Technology (SET) plan in response to the goal of achieving climate neutrality in cities. The plan includes action 3.2-Smart Cities and Communities, which involves collaboration among academia, industry, decision-makers, and civic organizations (JPI Urban Europe, 2018). Today, in different contexts that enable the achievement of goals at the local level, PED (Positive Energy District) is becoming a recognizable concept and is used in various EU program policies (Sassenou et al., 2024). PEDs were first defined as "*energy-efficient and energy-flexible urban areas which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy*" (JPI Urban Europe/SET Plan Action 3.2. (2020)). As such, PED is recognized as a potential starting point for achieving the goals of sustainable urban environments. At the same time, the potential relevance of PED is reflected in the fact that even within one municipality, there are substantial variations in energy demand and consumption between different districts (Lindholm et al., 2021). Accordingly, as a result of the SET plan, the Joint Program Initiative (JPI) Urban Europe PED Program was created with the ambition to develop a comprehensive process of reaching 100 Positive Energy Districts and neighborhoods in Europe, taking into account technological, spatial, regulatory, socio-economic, and environmental parameters (Urban Europe, 2025). The transition to sustainable energy at district levels should be carried out in accordance with the principles of a just

* Corresponding author.
E-mail address: jelenan@plan.aau.dk (J. Nikolic).

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Nomenclature

BS	Building Surrounding
EB	Electric Battery
EC	Energy Community
ED	Energy District
EE	Energy Efficiency
EN	Energy neighborhood
EU	European Union
EV	Electric Vehicles
HP	Heat Pumps
HR	Heat Recovery
LS	Lighting System
nZEB	nearly Zero Energy Buildings
P2H	Power to Heat
PED	Positive Energy District
PV	photovoltaic
RES	Renewable Energy Sources
SET	Strategic Energy Technology
ST	Solar Thermal
TES	Thermal Energy Storage
V2B	Vehicles to Battery
V2G	Vehicles to Grid
W	Wind
WtE	Waste to Energy
ZEB	Zero Energy Building

energy transition. A just energy transition ensures the fairness, availability and affordability of sustainable energy for all members of communities (Jame et al., 2022). However, in the scientific literature the term PED is not clearly determined, and 35 definitions have been identified concerning limitations and conditions to be met by PEDs (Brozovsky et al., 2021). The absence of a clear and precise definition of the term that represents energy changes in urban environments highlights the difficulties of analyzing the energy systems of urban districts. It is complex to define boundaries of energy consumption and production in PEDs, since their division is most often strictly geographical. The definition of PEDs in terms of geographical boundaries varies in the literature,[1] resulting in unclear PED sizes which can range from a group of buildings to islands or larger city districts (Derkenbaeva et al., 2022; Sassenou et al., 2024). Apart from the size, PEDs can be categorized according to how energy balance is achieved, depending on the place of production of the RES and the ways in which the PED interacts with surrounding energy systems (Fig. 1.), as (Albert-Seifried et al., 2022):

- *PED virtual*– energy production is not confined to the district's geographical boundaries, meaning that renewable energy sources (RES) can be installed outside the district. This definition allows for greater flexibility by utilizing renewable energy resources beyond the immediate boundaries of the district.
- *PED dynamic* – energy is produced solely within the geographical boundaries of the system, but there is interaction with the surrounding environment in terms of importing and exporting energy.
- *PED autonomous* – energy is produced exclusively within the system's geographical boundaries, with no interaction between the district and its surroundings. The district operates as an energy island, relying heavily on energy storage systems, primarily for electricity. This configuration emphasizes the need for significant capacity of batteries to balance production and consumption within the district due to temporal variations in production from RES and energy demands.

Each of these definitions is based on different initial assumptions of the system analysis that can be expected to result in different economic, urban and environmental criteria.

Also, the lack of a clear definition is a major obstacle in realizing the concept (Sassenou et al., 2024), because understanding the limits and framework is necessary to achieve a positive annual balance based on energy needs and local renewable energy production (Neumann et al., 2021). Whereas the energy balance is observed annually, the question is how credible this approach is, because, in practice, there is significant temporal variability in renewable energy production and energy demands. Although the example of annual energy balances makes it easier to achieve the goal of becoming a PED, the question is how applicable it is and whether it contributes to the improvement of grid resilience (Casamassima et al., 2022).

To bring the concept of PED to life and effectively facilitate energy transitions, it is essential to clearly define what it entails. Therefore, policies at this level should specify how and within what limitations RES can be produced, based on the size of the PED and the sectors it encompasses. As highlighted in a comprehensive review paper (Yang et al., 2025), insufficient integration among energy subsystems has been identified, underscoring the importance of developing a unified evaluation framework as a critical step toward the future implementation of PEDs.

In this regard, this paper examines the impacts of different PED frameworks on the behavior and sustainability of the future smart energy system of the city district. Smart energy systems were created to demonstrate the potential synergies among various subsectors by integrating new technologies and infrastructure. By combining different energy sectors, energy systems can enhance flexibility and more effectively manage the variability of RES, ultimately achieving a positive energy balance (Lund et al., 2017). To account for temporal variability, a case study is necessary.

In this paper Aalborg East, a city district in Denmark, is used as a case, to highlight mentioned aspects. From the perspective of PEDs, Aalborg East is of particular interest due to the presence of significant institutions such as a university campus, a university hospital, a sports center, schools, office spaces, and Denmark's largest cement factory, Aalborg Portland, the largest Danish standalone emitter of CO_2. This allows for analysis of the impact of inclusion/exclusion of different demands, to evaluate the concept of PEDs not only based on boundaries for energy production, but also for inclusion of energy demands. The general conclusions regarding the implementation of the PED concept can therefore be applied to urban environments with differing characteristics. Furthermore, the methodology presented in the paper is adaptable and applicable to any urban district.

2. Literature review

The forerunners of a PED are buildings with nearly zero (Nzeb)[2], net-zero consumption (ZEB) or even those in which more energy is produced than is consumed annually. By 2021, the energy systems of buildings had been the subject of research of a large number of scientific studies

[1] In the projects that were implemented within the Horizon 2020 program, a condition was set that PEDs include at least 15,000 m^2 of floor area (1872640-faq_scc01_(updated)_v10_en.pdf (europa.eu)).

[2] From 2030, the standard for new buildings will be raised from "nearly-zero energy buildings" (EU/31/2010, revised in 2018) to "zero-emission buildings" (EU2024/1275): Nearly-zero energy and zero-emission buildings - European Commission

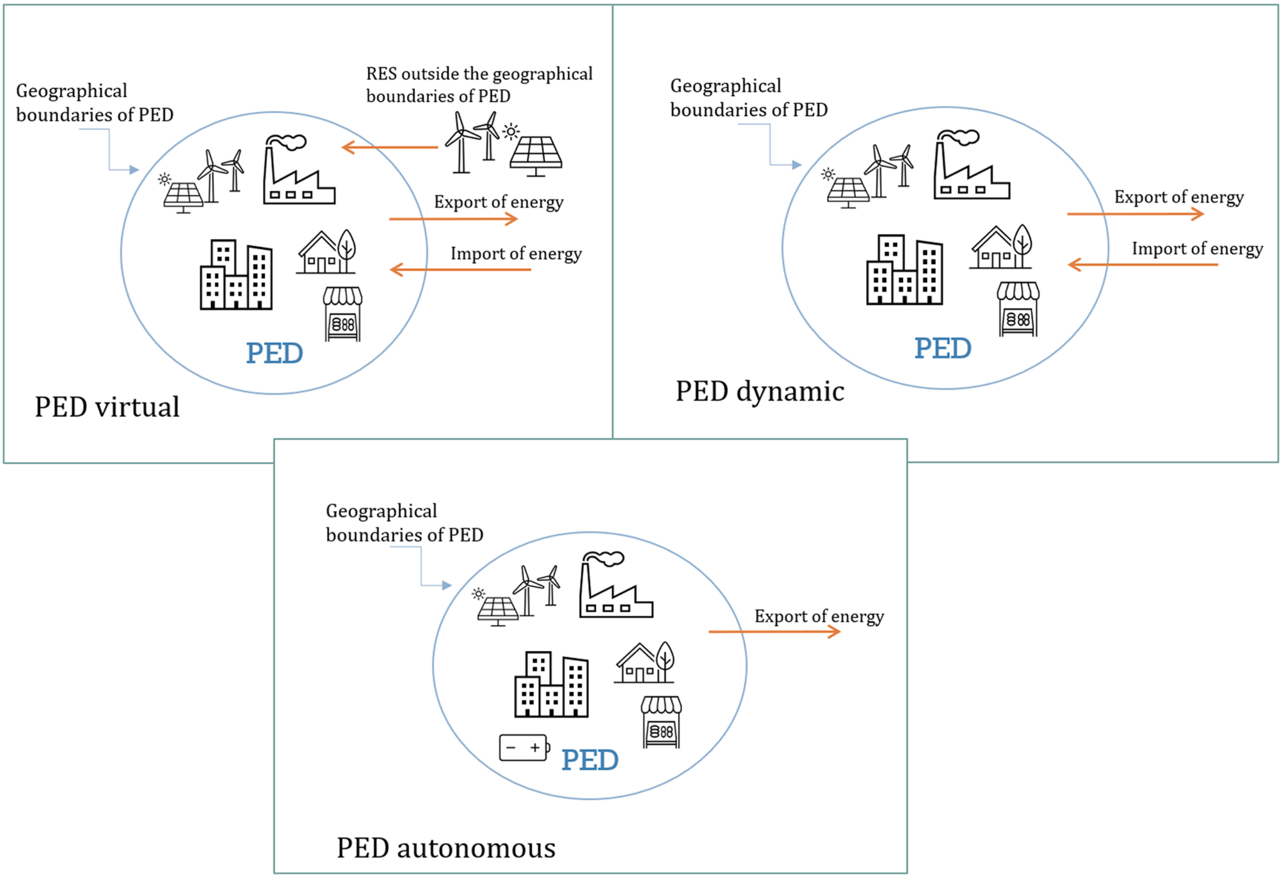

Fig. 1. Simplified representation of PED subcategories definition.

(>370) around the world (Kumar & Cao, 2021). Hence, including different energy sectors in the analysis can enable flexibility that is often impossible if energy production and consumption are observed only within one residential unit (Capuder & Mancarella, 2016). In this regard, it is necessary to bridge the gap between climate neutralization in the building and the realization of this goal at higher levels. As a result, the concept of energy-independent buildings was followed by broader concepts of net zero energy blocks,[3] or energy neighborhood. Although none of the approaches tend to achieve a positive energy balance, i.e. producing more energy than consumed, they are important in the analysis of future energy systems of PED (Heendeniya et al., 2020), because ultimately, a net-zero energy block could lead to a positive energy district (Blumberga et al., 2020). However, as shown in Table 1, the terms energy neighborhood (EN), community (EC), and district (ED) often have similar or identical meanings in the literature due to the lack of a clear definition, and they are often situated within the similar size geographical boundaries.

As can be concluded based on the presented examples of energy districts, they vary in their complexity, approach, implemented technologies and RES utilization (according to the PED subcategories definition). In some cases, the district represents a pair of connected buildings (examples (Samadzadegan et al., 2021; Famiglietti et al., 2023; An et al., 2023; Kim et al., 2019)), while in others it refers to a larger part of the city [28,32,40,42]. Therefore, examining the clear boundaries and consequences of PED on the energy system of a city or state is important. In scientific circles so far, it has been discussed whether the energy requirements of the infrastructure in districts should be taken into account, such as water and waste management, public lighting and office buildings, and it is observed that so far mainly the energy requirements in buildings have been taken into consideration (Hedman et al., 2021). In most published methodologies, achieving a PED begins with finding the most suitable part of the city (Sassenou et al., 2024) focusing on meeting the energy needs of highly energy-efficient buildings or upgrading existing buildings to near-zero energy or positive energy status. However, this approach limits the scope of the concept to only a small number of new buildings or specific parts of the city. As a just energy transition has to ensure that nobody is left behind,[4] PEDs would also have to include energy-inefficient buildings and those affected by energy poverty (Sassenou et al., 2025), because energy transition should be accessible to everyone.

Considering existing publications, energy modeling of energy districts with a temporal resolution is very limited. Most often, it is based on the analysis of only electricity needs in rural and urban districts (Bruck et al., 2021; Marrasso et al., 2023; Ahrens Kayayan et al., 2025; Michellod et al., 2025). Also, the implications of PED boundaries (virtual, dynamic, or autonomous) at the hourly level, as well as the consequences of imbalances between energy production and consumption demand were analyzed in Ochs et al. (2025). However, this study focuses exclusively on the building sector, including existing residential blocks with high energy efficiency. Also, only a few case studies analyze systems that are outside the framework of buildings, such as transportation (Castillo-Calzadilla et al., 2022), and the influence of industry (Marrasso et al., 2023) (Marrasso et al., 2024) on achieving PEDs. This

[3] Energy block represents at least 3 connected buildings

[4] "Leave No One Behind" (LNOB) is the core promise of the 2030 Agenda for Sustainable Development. It signifies the commitment of all UN Member States to eliminate poverty, end discrimination, and reduce inequalities that hinder individuals and humanity’s potential (Unsdg | Leave No One Behind).

Table 1
PED literature review.

Location	Type	Energy system/Scale	Implemented technologies	PED subcategories	Reference
Rome, Italy	ED	10 buildings, 100 dwellings and 188 vehicles (9950 m^2)	PV, TES, EB (different scenarios)	dynamic	(Pastore, 2023)
Valencia, Spain	ED	Urban waterfronts (134.65 km^2)	PV, W, EB (different scenarios) and LS	dynamic	(Aparisi-Cerdá et al., 2022)
Hong-Kong, China	ED	30-floor office buildings and 30-floor hotel building	EE, PV, W, V2B, V2G (different scenarios)	virtual	(Zhou et al., 2021)
Lisbon, Portugal	ED	Residential building stock, 1863 buildings	EE, PV	dynamic	(Gouveia et al., 2021)
Herrera, Panama	ED	34 houses (11,300 m^2)	EE, PV	dynamic	(Chacón et al., 2022)
Belgium	EN	Buildings and daily mobility (2 case studies- 9700 m^2 and 57 buildings; 120,200 m^2 and 55 buildings)	EE, PV, W, EV, ST	dynamic	(Marique & Reiter, 2014)
Fictive place with cold northern climate	EN	1300 residential units (22,000 m^2)	EE, PV, W, TES, WtE	autonomous/virtual	(Hachem-Vermette & Singh, 2020)
Spain	ED	Buildings, electric mobility	EE, PV, HP, EV, LS, EB	virtual	(Castillo-Calzadilla et al., 2022)
Utrecht, Netherland	EN	40 net-zero buildings	PV, HP	dynamic	(Kazmi et al., 2022)
Macau, China	ED	Building sector	EE, PV	dynamic	(Li et al., 2016)
Herrera, Panama	ED	34 houses	EE, PV, BS	dynamic	(De León et al., 2023)
Valencia, Spain	EC	164 buildings, 6388 properties (568,971 m^2)	PV, HP, HR	dynamic	(Masip et al., 2023)
Dhaka, Bangladesh	EC	96 flats	PV, W, HP, Biomass	dynamic* *only electricity	(Zeyad et al., 2023)
Montreal, Canada	ED	6 buildings	PV, HP, EB	dynamic	(Samadzadegan et al., 2021)
Denver, USA	ED	University Campus, +100,000 m^2	Biomass, PV, HP, EB, HR	dynamic	(Saarloos & Quinn, 2021)
Milan, Italy	ED	14 buildings	EE, HP, HR, PV	dynamic	(Famiglietti et al., 2023)
South Korea	EC	2 residential buildings, 2 office buildings	EE, PV, ST	dynamic	(An et al., 2023)
Jincheon, South Korea	EC	6 public buildings, 72,000 m^2	TES, HP, ST, PV	dynamic	(Kim et al., 2019)
Los Sauces, Island La Palma (two PED cases-rural and urban sites)	ED	Both sites with floor area of app. 15,800 m^2	PV, EB	dynamic	(Bruck et al., 2021)
				*only electricity in perfect climate with no need for heating/cooling	
Italy	ED	Mixed-use building	PV, Wind	dynamic* Only electricity	(Marrasso et al., 2023)
Ireland	ED	University Campus	EE	Dynamic *analysis was done to show how transformation inside PED can effect CO_2 reduction	(Pierce et al., 2024)
Italy	ED	Sector service and office building, wastewater treatment plant and residential buildings (1418 m^2)	Wind, PV, Hydrogen	dynamic	(E Marrasso et al., 2024)
Lagos, Nigeria	ED	50 houses	EE, PV, LS,	dynamic	(Atiba & Chwieduk, 2024)
Sweden	ED	560 apartments	HP, PV, HR	dynamic	(Ahrens Kayayan et al., 2025)
Romania	ED	447 buildings	EE, PV	dynamic	(Ciulla et al., 2025)
Switzerland	ED	building stocks	PV, HP and EV	Dynamic (only electricity)	(Michellod et al., 2025)
Italy	ED	4 University buildings	EE, PV	dynamic	(Di Pilla et al., 2025)

approach results in limited literature results regarding the possible complexity of the PED system. Although industry plays a significant role in the life and dynamics of urban areas, the questions arise whether its high energy requirements prevent the achievement of PEDs (Hearn & Castaño-Rosa, 2021); whether its exclusion from the analyses is justified and whether it leads to a fair distribution of energy requirements in the processes of decarbonization of society. Namely, if PEDs are observed as pieces of a puzzle that will speed up the decarbonization process in cities, by omitting the whole sector, a part of the whole is missing. Also, local balancing and utilization of energy surpluses via sector coupling can enable maximization in the use of RES, which is why the interaction between different parts of the energy system is important (Backe, 2019). Therefore, analyzing all types of energy demands in the PED, which involves a complex structure and interconnection between sectors, poses a significant challenge.

Although there is a growing interest in PEDs in scientific circles, analyses of their potential are unevenly distributed. A paper that presents results from a study of state of the art literature shows that most of the identified publications refer to the analysis of energy systems in Norway, Italy, Belgium, Germany, Sweden, Spain, Finland, and the Netherlands, while outside Europe the most analyzed PEDs are in China (Brozovsky et al., 2021). Different weather conditions, energy consumption patterns, and energy costs can result in different PED outcomes (Bruck et al., 2022). Therefore, analyses of individual cases are important, because PED does not only mean the use of existing technologies but is based on examining the synergy of new technologies and the characteristics of each urban environment individually (Sareen et al., 2022). Even in environments with identical buildings, consumption can vary depending on occupant behavior (Kazmi et al., 2022).

Consequently, analyzing new case studies is important since each energy system has its own characteristics, which can contribute to improving the general understanding of the concept and help in paving the decarbonization pathway.

Therefore, this paper aims to explore the size, sector integration and the technical effects of the different PED definitions. Accordingly, the main novelty and contributions of this study are as follows:

1) Comparing the impact of different definitions of PED (virtual, dynamic or autonomous) in terms of system boundaries on economic, energy mix and import and export energy balance.
2) Determining the relative importance of various energy sectors, including industry, and its consequences on the possibility of reaching the concept of a PED.
3) Presenting a case study of a PED, thereby contributing to the expansion of the catalog of knowledge in the research area.

This paper contributes to Sustainable Development Goals 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production) and 13 (Climate Action).

3. Methodology

The European Commission has acknowledged the establishment of PEDs as a significant opportunity to enhance the decarbonization of cities. Therefore, it is important to offer a clear method for implementing this concept, so it can be applied effectively and become generally acknowledged.

Accordingly, this paper aims at investigating the implication of varying definitions of size and subcategories of PEDs on the feasibility of achieving PED status. To conduct this analysis effectively, it is crucial to delineate the limitations and boundaries within the context of the local district.

The methodology, presented in Fig. 2, employs a two-step analysis to assess the complexity of PED. Initially, various scenarios were examined to evaluate how different energy sectors (industry, transportation and building) influence the energy demands of future PEDs. Subsequently, for each scenario, the feasibility of implementation, economic impact and energy import/export balance were analyzed for the corresponding definition of sub-scenarios: PED virtual, PED dynamic, and PED autonomous.

The significance of this methodology is reflected in the establishment of a clear approach, which can be replicated to PEDs all over the world. At the level of smaller-than-national units, the definition of energy system boundaries is of utmost importance, as only a comprehensive approach can contribute to the establishment of climate neutrality, both at the district or city level, as well as at the regional and national levels.

To apply the proposed methodology shown in Fig. 2, the current energy demands of the analyzed district must first be established. In this research, the energy district is defined by postal code to capture the complexity of the system and include all relevant energy sectors. Some energy demands should be understood beyond the specific district, and as such current energy demands in industry and transportation sectors are defined based on principles of a fair distribution of energy demand within the country. Namely, the demand for electricity, as well as fuels used in industry and transportation, should be defined based on the share of the district's population in relation to the total national energy demands in these sectors (Thellufsen et al., 2020). This approach relies on a fair share of energy demand across the mentioned sectors, as industrial products are widely used at both national and international levels, even though industrial production demands are tied to a specific location. Likewise, transportation should be considered in the same way, including international transportation, since people and goods move beyond the boundaries of the district, crossing its geographical limits. Correspondingly, in the case of centralized energy production systems within a district, the amount of energy attributed to the district shall correspond to the PED's share of the population.

On the other hand, heating demand for households, public buildings, and office spaces is determined according to the real heating requirements, based on the actual hourly distribution demand throughout the year, as heating is inherently a local energy demand, though production can cross the border of the defined district via district heating grid.

In the case study under consideration, industrial cooling demands are included within the overall electricity demand. However, in countries where there is a significant cooling demand for building sector, the same principles used for determining heating demand should be applied. This approach may enable further analysis of cooling systems, such as the integration of district cooling.

The focus is on current energy demand in the majority of state-of-the art studies of PED, as presented in Table 1, but the establishment of urban decarbonization is a long-term process, and changes in residents' energy consumption behavior can be expected over time. At the same time, PEDs need to be able to meet the projected future energy demands, defined in accordance with national energy objectives. Hence, general principles need to be established to ensure that the future PED adheres to the principles of fair energy distribution across all sectors and aligns with national energy goals. These principles are summarized in Table 2, which outlines the modeling assumptions for each PED sub-scenario.

Applying the principles, scenarios involving various energy sectors have been analyzed:

Scenario 1 covers the total energy demands of all energy sectors (industry, transportation and buildings), based on the projection of a national goal and strategic energy development document. As the PED frameworks are unclear, it is questionable whether the transportation sector should be within their boundaries. In addition, in the new draft Framework for Positive Energy Districts (Haindlmaier, Reiter, & Hinterberger, 2024) there is a critical review of the inclusion of the transportation sector in the scope of PED. On one side, globally, transportation is an energy-intensive sector based on the use of fossil fuels (International Energy Agency, 2025); on the other, the energy consumed in transportation by the residents in the area often lies outside the defined boundaries of the PED. This prompts a critical inquiry: if the PED is expected to fulfill energy demands within its own framework, relying solely on local energy production, can it also be assumed to satisfy the energy needs that occur outside this system? Therefore, a scenario that does not include transportation was also analyzed.

Since in literature so far, energy districts most often do not include industry, two industrial scenarios have been analyzed. In **Scenario 2** the fuel demand for technological processes in industry is neglected, but industrial need for electricity and heating, as well as their consumption patterns are considered. In **Scenario 3** the electricity demand for industries is neglected, but industrial heating demand is considered, since thermal energy is most often produced and used locally and plays a significant role in the dimensioning of the district heating system. Both scenarios cover heat and electricity needs in households, the public sector and the service sector.

Finally, this paper shows the consequence of the implementation of all PED sub-scenarios on the **Scenario 4** that has so far been most used in literature in which only the energy needs of households are considered.

As the energy analysis is conducted on an hourly basis, depending on the energy demand and supply in all sectors, PED will export the surplus energy to the grids in the form of heat or electricity during periods when the system produces more energy than required. In cases where the energy demand exceeds the amount of energy produced, the system will import the necessary energy to meet the demand. In the current electricity market, the increased integration of RES, especially PV, is expected to result in a negligible income from energy exports due to the harmonized production of PV surpluses energy in daylight hours. On the other hand, the price of electricity imports is determined based on the Danish Energy Agency Energy price assumptions for 2045 (Energistyrelsen, 2022), adjusted in accordance with the profiles of the current production of variable RES. The prices of the energy systems of the future PED are defined in accordance with the assumed future investments and operating and maintenance costs presented in the Technology data catalog developed by the Danish Energy Agency

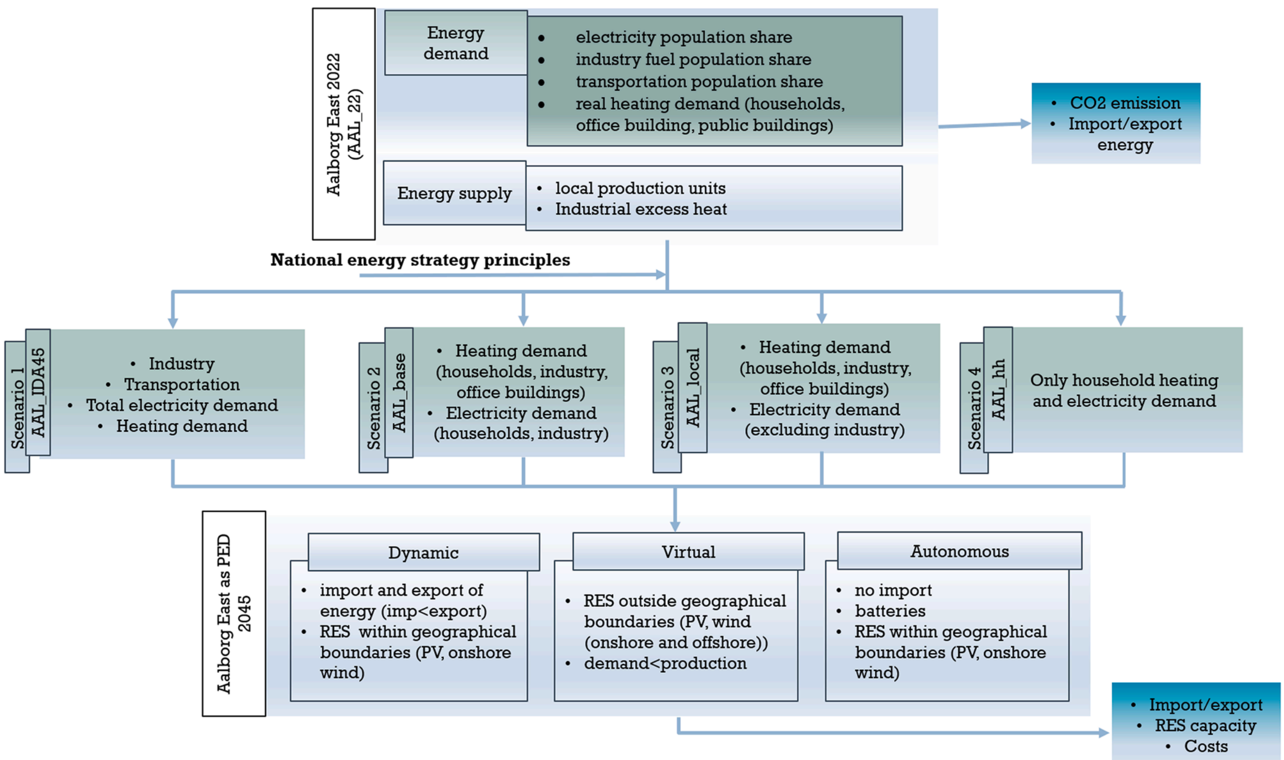

Fig. 2. Applied methodology for analyzing the effect of different definitions of PED.

Table 2
Principles for modeling PED sub-scenarios.

	PED		
	Virtual	Dynamic	Autonomous
Geographical boundaries for RES installation	Outside PED	ZIP code of PED	ZIP code of PED
RES capacity	All RES (share defined based on the population for all RES covered by the national energy development strategy)	Territory-specific RES in the observed district. Condition: PV must first be installed on available roof surfaces. PV capacities until the condition that import<export is met.	Territory-specific of PED
Battery capacities	None	None	Until the condition that Import=0 is met
District heating	In all future scenarios the district heating temperature is expected to go to typical 4th generation district heating temperature levels, meaning 55–65 °C in the supply and 25–30 °C in the return. These temperature levels mean that the waste heat from electrolysis can be utilized directly, where applicable, as this is expected to be in the range of 50–80 °C (Danish Energy Agency, 2017).		

Notes: In the analysis, hourly production from RES and hourly energy demand are considered. The software used (EnergyPLAN) considers the variability of all RES and real-time weather data (detailed in Section 3.1). In the analysis of PED dynamic, energy will be imported into the system when there is no production from locally available RES, as the system always first uses the electricity it produces itself. The future energy demands, including electricity demand, is based on Smart Energy Denmark scenario (Lund et al., 2021b). This includes that 25 % of the electricity demand is expected to flexible demand and to extend be able to respond to variable renewable.

(Energistyrelsen, 2025). The expected costs of implementation, maintenance and operation, the expected service life for all technologies used, as well as the prices of fuels are shown in Appendix A of work (Table A.1.).

The proposed methodology was applied to the case study of Aalborg East.

3.1. Energy system analyses tool used - EnergyPLAN

To understand sector coupling options and temporal effects of the PED, an energy system tool must be applied, including all energy sectors and simulating in a sufficiently high temporal resolution. The behavior of the Aalborg East energy system is simulated using the EnergyPLAN software (Lund et al., 2021a). EnergyPLAN is a simulation tool that encompasses all sectors of the energy system (electricity, industry, transportation, heating and cooling systems), as well as energy conversions (Fig. 3). EnergyPLAN has been used in numerous studies of various energy systems. By 2022, EnergyPLAN had been used in 315 peer-reviewed articles to analyze the local, national or multi-country level (Østergaard et al., 2022).

To achieve the principles of Smart Energy Systems, EnergyPLAN facilitates energy exchange through intersectoral connectivity during all hours of the year. In this analysis, the technologies included are: heat pumps, boilers, centralized systems for electricity and heat production, RES, gasification, and for the Scenario 1, also electrolysis and CO_2 capture units. After the user has defined the capacities of production units, system losses, and hourly energy demand/supply, EnergyPLAN provides data on the energy balance over the course of a year, primary energy usage, CO_2 emissions, and costs. The simulations conducted in this study are based on technical simulations in which priority is given to electricity primarily generated on locally available RES. In the example of the analyzed district, the technical simulation approach is primarily based on determining the priorities of production units in the district heating system. In this procedure, in the example of the analyzed district, the use of industrial waste heat has priority, followed by the use of

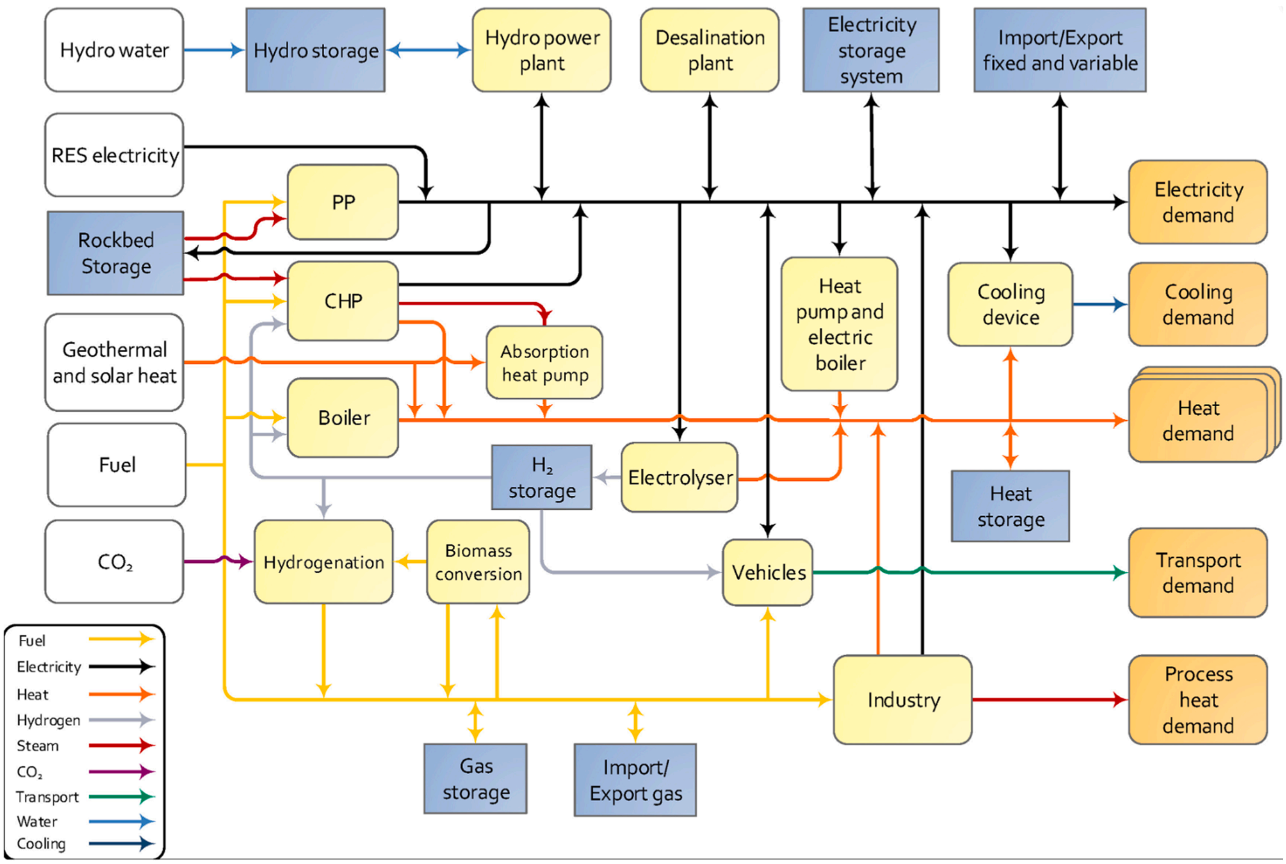

Fig. 3. Overview of smart energy system technologies and their interconnection on which EnergyPLAN is based (image adopted from the reference (Lund et al., 2021a)).

heat from waste incinerators. To increase the local use of RES and to reduce its output, the use of heat pumps will be preferred at times when electricity production is abundant. The increased use of heat pumps results in reduced electricity generation from combined heat and power production (CHP) due to a reduction in the heat load. On the other hand, in a situation with unused CHP capacity, heat storage is used, which serves to enable the maximum utilization of heat capacities, the use of electricity and the reduction of electricity exports. In the case of electrolysis in the system, the electrolysis is assumed to be used for hydrogen production, when there is an excess of electricity in the system and the hydrogen can be stored. Waste heat from electrolysis can be utilized in the district heating system. With electricity storage, the storage will be charged when there is excess electricity in the system that cannot be used for the above-mentioned processes, and when the system is discharged it will result in a decrease in electricity import and a decrease in production from electricity units that use fossil fuels. As the final step of this type of simulation, the reduction of electricity exports can also be achieved by reducing the production of renewable energy, reducing the production of CHP while increasing the production of heat from peak boilers, or replacing fossil fuel boilers with electric boilers. The user can define the order in which these measures are established.

4. Case study description

Aalborg East is a suburb of the Danish city of Aalborg, with the postal code 9200. A picture of the area is shown in Fig. 4.

This part of the city began to develop from a rural area to become part of the city of Aalborg during the late 1960s and 1970s. Today Aalborg East continues to grow, with a 10 % increase in the number of residential units in 2023 compared to 2014. This area features a diverse building stock, including single-family houses, terraced housing, housing estates with apartment blocks, and a mix of owner-occupied and rented housing, alongside holiday houses and farmhouses, with a population of approximately 20,000 (Aalborg Kommune, 2024). The most prevalent construction period is between 1970 and 1980 (37 %), while 18 % of the existing buildings were constructed after 2011 (Aalborg Kommune, 2024).

For the purposes of fair energy distribution across sectors, as outlined in the methodology, the Table 3 presents a comparative overview of the population in Denmark, Aalborg Municipality, the city of Aalborg, and the Aalborg East district.

4.1. *Energy demand of future PED of Aalborg East*

Based on the defined principles of fair energy distribution in the industrial and transport sectors, as well as the energy demands in the household and office and service building sectors, the total energy demand of Aalborg East for the reference year 2022 has been determined. Further information on the energy balance, including demand-supply and system losses, is available in Appendix B (Table B.1).

As the future energy district can be expected to develop in accordance with national goals, certain principles need to be adopted. For the case of Aalborg East, future energy demands are defined based on principles outlined in the IDA Climate Response 2045 (Lund et al., 2021b) (IDA 2045). This scenario was created in a close collaboration between researchers from Aalborg University and the Danish Society of Engineers (IDA). The aim of the document is to propose an ambitious scenario that enables the achievement of the national goal of establishing the first fully renewable and decarbonized society by 2045 (Lund et al., 2022).

Transferring the principles from this national scenario to the district of Aalborg East, the following assumptions have been made:

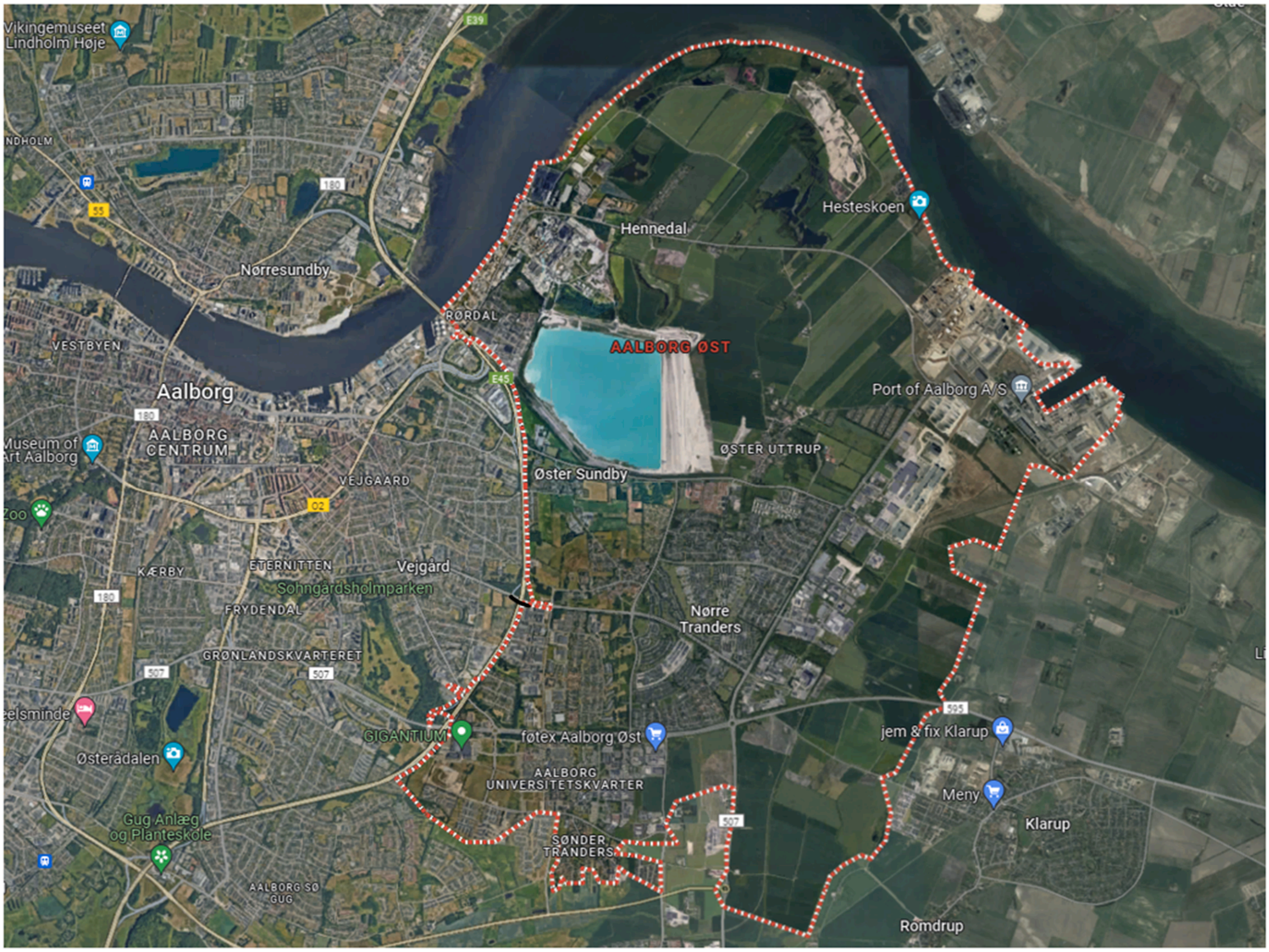

Fig. 4. Aalborg East district.[5]

[5] Adopted from Google Maps, https://www.google.com/maps.

- Households not connected to the district heating system or not deemed relevant for connecting to district heating will replace individual heating units with individual heat pumps.
- A 30 % reduction in heat demand is expected in individual households e.g. via increasing insulation.
- The heat demand for the district heating system is determined based on a 30 % reduction in current household consumption, while also accounting for the expected increase in energy demand due to the anticipated construction of new residential units, as well as the heat demand share in industry.
- Waste incineration is expected to decrease by 50 % due to anticipated increases in recycling rates.
- The availability of biomass is defined based on the sustainable biomass share at the EU28 level of 27 GJ/capita annually (Lund et al., 2022).

Table 3
Aalborg East statistical data for reference year.

Area	Population	Reference
Aalborg East	Approximately 20,000	(Aalborg kommune, 2024)
Aalborg City	120,914	(Denmarks Statistik , 2024)
Aalborg Municipality	225,571	(Denmarks Statistik , 2024)
Denmark	5965,990	(Denmarks Statistik, 2024)

- Heat pump capacity in district heating is dimensioned to cover the yearly average district heating demand in Aalborg East and a heat storage capacity for 14 days with an average heat load. This choice of heat storage is justified by the results presented in the paper in which the impact of heat storage on future smart energy systems was examined. At the Danish national level, it will be economically feasible for future energy systems to install a between 100 −200 GWh heat storage (Christensen et al., 2024), which corresponds to the share proposed in the paper.

A comparative overview of the current energy demands of the system and the projected future energy demands across different sectors in Aalborg East for the year 2045, in accordance with the IDA 2045 national goals, is presented in Table 4.

4.2. Energy supply of future PED of Aalborg East

In Aalborg East, households, public buildings, and offices are primarily connected to the city's district heating system. As a highly energy-intensive cement industry is in this part of the city, the district heating system is mainly supplied by waste heat from Aalborg Portland. The total energy demand of this facility is equivalent to 12 % of the total industrial energy demand in Denmark, while the population share of Aalborg East of the total population of Denmark is 0.34 %. Consequently, to achieve the equity principles outlined in Section 3., the

Table 4
Aalborg East Energy demand in 2045.

Sector	subsector/fuel	GWh/year		
		2022		**2045**
Electricity	Households	46.28		32.58
	Industry & service	102.35		71.84
	Industry, additional electricity demand	-		40.29
District heating	Households	33.07		29.49
	Industry & service	125.19		108.07
Individual heating systems	Fuel boilers	15.39		-
	Heat pumps	0.43		12.66
Industry	Grid gas	23.64		11.61
	Biomass	16.4		11.61
	Other fuels	39.95		-
Transportation	Jet Fuel	0.73	electrofuels/ HTL/Pyrolysis	39.21
	Diesel and biodiesel	100.83		21.5
	Ammonia	-		12.43
	Petrol/Methanol and biomethanol	52.71		4.1
	Natural gas	0.35		-
	Hydrogen	-		4.1
	Electricity (dump charge)	2.35		24.35
	Electricity (smart charge)	-		27.18

energy demand of Aalborg Portland is included in the overall industrial demand of Denmark and is distributed evenly. On the other hand, waste heat can only be used locally, and Aalborg Portland provides enough waste heat to cover the heating demand of 25,000 households (Aalborg Portland Cementir, 2019). However, since this energy is not distributed exclusively to Aalborg East, but is available to all buildings connected to the district heating grid of the city of Aalborg, and in line with the equitable distribution of energy demand, only the share based on the population of the analyzed district relative to the total population of Aalborg city will be considered.

In addition to the cement factory, a waste incineration plant (Nordværk) with a combined heat and power production is located in Aalborg East. This incineration plant processes residential waste and primarily collects waste from Aalborg Municipality and the surrounding municipalities in the North Jutland region. Therefore, the total amount of heat and electricity supplied to the Aalborg East grid is determined based on the share of population of the analyzed district, with the assumption that all citizens produce a similar amount of waste. To highlight the impact of the PED's geographical boundaries on the energy balance, Table 5 presents the total amount of waste heat from Portland and the heat and electricity generated by the waste incineration plant, as well as their share in Aalborg East.

As for electricity generation within the geographical boundaries of the analyzed district, besides the electricity produced by the Aalborg incineration system (Nordværk), there are no other producers within the district, neither centralized energy production units nor significant RES

Table 5
Energy distributed to the grid from Nordværk and Aalborg Portland.

	Total energy [GWh/year]	Aalborg East share [GWh/year]	Comments
Waste incineration-Electricity production	136.19	11.27	Share of Aalborg East population in Aalborg Municipality
Waste incineration-Heat production	445.81	36.88	
Waste heat from Aalborg Portland	300	49.62	Share of Aalborg East population in Aalborg City

such as PV rooftops or wind. The shares of Aalborg East in the distribution of industrial waste heat (as presented in Table 5), as well as the shares of energy production from the waste incineration plant, remain consistent across all scenario analyses.

As previously stated, the future energy system should align with national targets. In this regard, Table 6 presents the planned RES capacities at the country level and their respective shares in the observed district of Aalborg East. To meet the previously discussed fairness criteria and to achieve a PED virtual, the installed capacities must remain within the ranges specified for Aalborg East.

For the future system analysis, both in the cases of PED dynamic and autonomous, the potential of PV was determined using GIS for mapping all the available rooftops larger than 500 m^2 in Aalborg East, whose areas was estimated at 0.82 km^2, with an estimated potential electricity production of 44.5 GWh[6] (Mathiesen et al., 2017). Furthermore, considering the district's characteristics, it is feasible to install 6 MW of wind turbines.

5. Results and discussion

5.1. Aalborg East as a PED: reference scenario and scenario 1 based on IDA climate response 2045 including all energy sectors

In accordance with the principles of fair energy distribution explained in the Methodology section, the city district of Aalborg East demonstrated a significant reliance on fossil fuels in the reference year 2022, particularly within the industrial and transportation sectors, as well as in energy imports. Existing energy conditions can be attributed to the lack of installed RES capacity (Fig. 5).

The 2022 reference scenario has been used as a starting point for creating the future Scenario of the analyzed district for 2045 (Scenario 1:AAL_IDA45), based on the principles presented in *IDA Climate Response 2045,* as explained in the Methodology and Case description. Compared to 2022, the Scenario 1 model for 2045 anticipates a transition from fossil fuels and an increased demand for electricity across all energy sectors. In this future energy scenario, individual heating systems have been replaced by heat pumps, and heat pumps are also installed into the district heating system. Electricity is generated also from RES outside the system according to the fair share of expected production.

Additionally, the decline in energy generated from waste incineration is due to a reduction in waste production, driven by anticipated improvements in recycling rates.

The analysis presented in the energy flow diagram (Fig. 6) highlights the potential for establishing a PED virtual, where technologies can be located outside the PED area. The findings reveal that with the fair share of RES the demand for electricity imports exceeds the export ability. This can be explained by the fact that smart energy systems, which are based on cross-sectoral integration, strive to maximize the use of produced renewable energy and minimize their exports. Also, the scenario

Table 6
Expected RES capacity and production (including biomass), for Denmark and (theoretical) Aalborg East share according to IDA 2045 national goals.

	Denmark		Aalborg East share	
	MW	TWh/year	kW	GWh/year
wind	5000.00	16.13	17,074	55.08
offshore	14,075.00	61.00	48,062	208.30
wave	132.00	0.46	451	1.57
PV	10,000	12,000		40.98
biomass		40.67		138.89

[6] Due to the shades, the position of the roof and the possibility of installing PV panels, half of the total area of the roofs were considered.

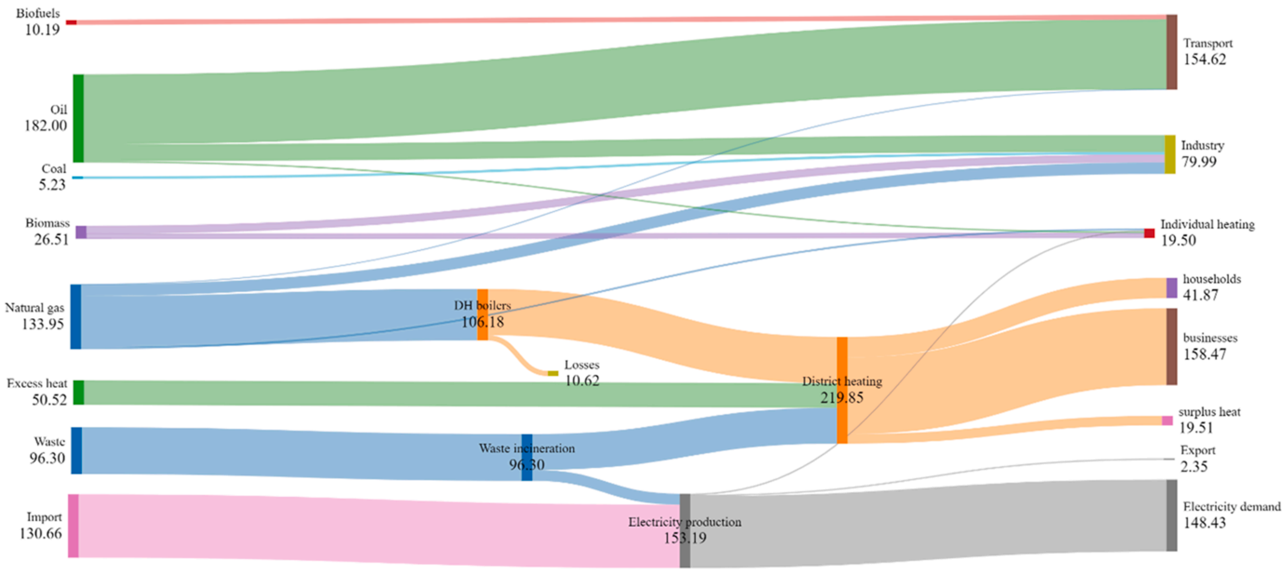

Fig. 5. Sankey diagram of the Aalborg East 2022 reference model.

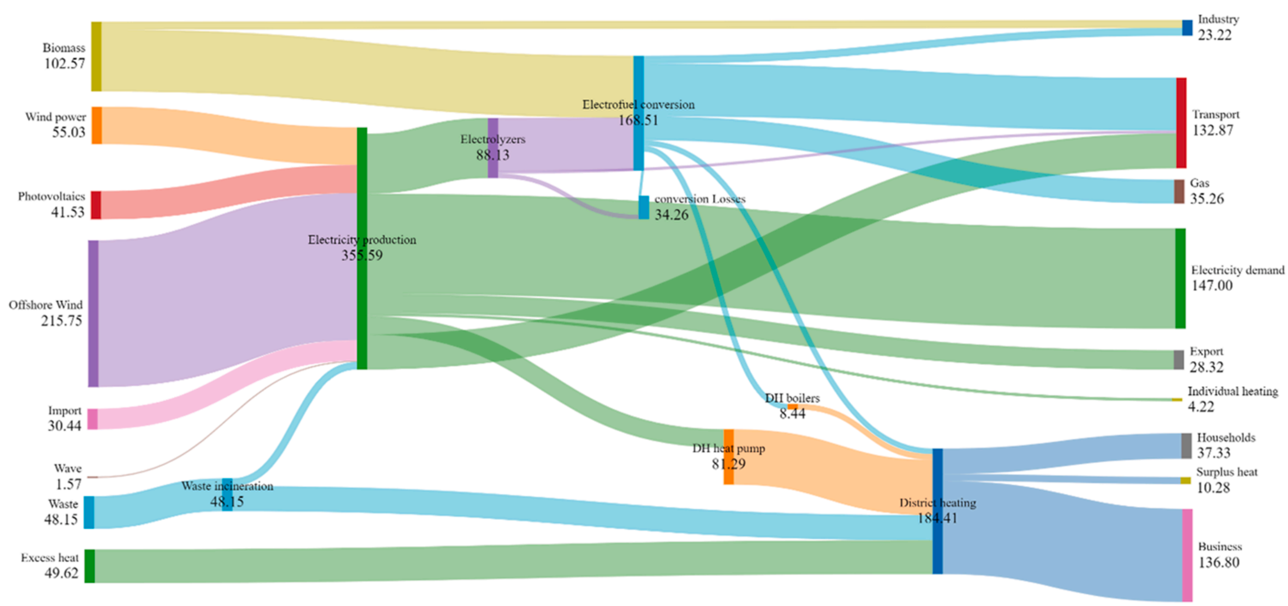

Fig. 6. Sankey diagram of Aalborg East's energy system based on the IDA45 (Scenario 1).

analyzed does not include the possibility of interconnection with other systems for the purpose of energy storage. Consequently, if only renewable energy production is considered in the energy balance, it is impossible to achieve the concept of PED in systems that include both the transportation and industrial sectors, even if it involves the production from RES outside the geographical boundaries of the analyzed system. To meet the PED in this scenario, it is necessary to install RES capacities that exceed the capacities defined by the principle of fair distribution, as shown in Table 7. For example, the concept of PED virtual can be achieved by installing an additional 1 MW onshore wind turbine.

If the transportation sector is neglected in the analysis of Aalborg

Table 7
Aalborg East as a PED: reference scenarios for 2022 and 2045 based on IDA45.

		Reference scenario 2022	AAL_IDA2045_virtual (Scenario 1_virtual)	AAL_IDA45_dynamic (Scenario 1_dynamic-transport excluded)
Fossil fuels		107.06	-	-
Biomass		127.74	171.33	171.33
Wind offshore		-	215. 75	-
Wind onshore	GWh/year	-	55.03	19.35
PV		-	41.53	135.61
Import electricity		130.7	30.44	134.48
Export electricity		-	28.32	39.74

East, and energy production is restricted to the available RES within that area, it becomes evident that the district cannot achieve a PED dynamic status. This remains the case even if the installation of PV capacities significantly surpasses previous estimates of rooftop limits as outlined in Table 6. Comparatively, 50 % of all rooftops with the area larger than 200 m^2 correspond to the installed power of PV panels of 47 MW.

It can be concluded that when the industrial and transportation sectors are within the boundaries of the future PED, it is necessary to approach the import and export of energy based on the annual balance of all energy sources, with the possibility of using RES from production capacities that are not only geographically limited but are based on established shares by the number of inhabitants.

The findings suggest that although Aalborg East includes both energy intensive industry and transportation, the energy needs for fuels should be excluded from the analysis to make the concept of PED viable. Meeting the energy demands of these sectors is often unfeasible within the geographical limits of the district, primarily due to constraints related to climate conditions and the limited capacity for installing RES. As such, these energy requirements should be evaluated from a broader perspective, encompassing energy scenarios at the level of entire cities or regions. This approach should align with national energy goals, viewing PEDs not as isolated energy systems but as integral components of a larger framework that can help achieve these objectives.

5.2. Aalborg East as a PED: scenario 2 with industry heating and electricity demand

Consequently, further analyses of the possibilities of achieving PED presented in this paper limit the use of energy in the industrial sector. When the industrial sector is reduced to electricity and heat energy demands only, while ignoring the fuel demand of technological processes (Scenario 2: AAL_base), Aalborg East can become a PED, either as a PED virtual or as a PED dynamic (Table 8).

However, the realization of the PED dynamic, in this case, triggers questions of rules and agreements of urban planning since the installation of the necessary capacity of possible RES, in this case PV, requires significant areas (1,1 km^2), which exceed the potential of roof structures.

5.3. Aalborg East as a PED: scenario 3 with industry heating demand

Moreover, while addressing the heat demand within the geographical boundaries of the PED, including the heat and electricity demand of service sectors and households, the electricity requirements of the industrial sector are totally disregarded and this makes the realization of the PED context more feasible (Scenario 3: AAL_local), as shown in Table 9.

In this scenario, a virtual PED can be achieved by significantly reducing the import and export of electricity beyond the system boundaries. PED virtual allows offshore wind production, which contributes to a more consistent production of electricity throughout the year. Conversely, a dynamic PED can be established by increasing energy imports during the winter and exporting surplus energy in the summer (Fig. 7).

Table 8
Aalborg East as PED in the case when the energy needs for production processes in industry are neglected.

		AAL_base_virtual (Scenario 2_virtual)	AAL_base_dynamic (Scenario 2_dynamic)
Biomass	GWh/ year	99.35	126.81
Wind offshore		107.2	-
Wind onshore		19.35	19.35
PV		40.81	135.82
Import electricity		26.28	74.02
Export electricity		30.7	74.19

Table 9
Aalborg East as a PED in the case in which the electricity demand of the industry is neglected.

		AAL_ local_virtual (Scenario 3_virtual)	AAL_local _dynamic (Scenario 3_dynamic)
Biomass	GWh/ year	111	128
Wind offshore		51.6	-
Wind onshore		29	19.35
PV		41.4	95.02
Import electricity		21.03	49.54
Export electricity		23.56	49.54

However, within such a limited system, achieving a self-sufficient PED autonomous is not feasible. This limitation arises because RES production relies heavily on electricity generated from PV, as shown in Fig. 7, leading to a substantial need for battery storage capacity. To achieve this status, it is necessary to have an installed system that exceeds the capacity of 20 GWh of battery, which is neither economically viable nor feasible.

5.4. Aalborg East as a PED: scenario 4 with household energy demand

Finally, if the analysis of Aalborg East as a PED is approached using the most common methodology in the literature to date, looking at heat and electricity needs only in households (Scenario 4: AAL_hh), it becomes economically and technically easier to achieve the concept of PED in the analyzed environment (Table 10).

However, PED autonomous as a concept in this part of Europe is unjustified. It creates fragmentation, as PED is not integrated into a broader energy system and fails to align with the national strategy. This lack of coherence results in significant PV production and inefficient battery usage. Consequently, the system becomes extremely expensive compared to the other two PED types and it can be expected that it will contribute to network congestion during summer.

Moreover, weather conditions at the analyzed site are characterized by short days during the winter, when the need for thermal energy is most pronounced. It can be assumed that a scenario in which the same system is located under different climate conditions could result in lower import emissions and lower demand for battery capacity, e.g., in conditions with a more even PV production throughout the year, which may be the subject of future analysis.

5.5. Overall comparison

Since the concept of PEDs is at the early stages of development, more case studies are needed to create effective strategies and regulations suited to the specific climates and conditions of each PED. In the example of Aalborg East, for which the results of a comparative analysis of all scenarios are shown in Fig. 8. and Fig. 9., the inclusion of different energy sectors allows for the application of different definitions of PED, all with the aim of achieving a PED. Energy flow diagrams for all scenarios, as well as their characteristics, are presented in Appendix C.

As can be seen, in the examined case study, the concept of PEDs could be most effectively realized through PED virtual. This approach facilitates the use of RES not only within the immediate geographical vicinity but also beyond the confines of the studied district, which results in less PV capacities, improved energy utilization and a decrease in both imports and exports of electricity. When energy-intensive sectors are

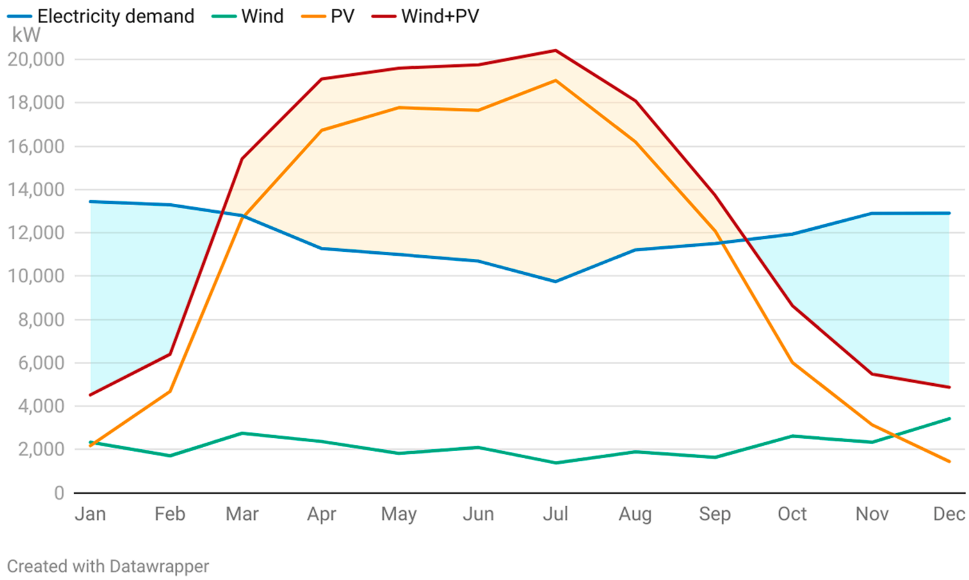

Fig. 7. Monthly electricity demand compared to monthly PV and wind production in the Scenario 3: AAL_local dynamic scenario.

Table 10
Aalborg East as PED in the case in which only household is included.

		AAL_hh_virtual	AAL_hh_dynamic	AAL_hh_autonomous
Biomass		48.15	48.15	48.15
Wind offshore		-	-	-
Wind onshore	GWh/year	29	19.35	19.35
PV		6	16.45	114.75
Import electricity		7.8	9.1	0
Export electricity		8.1	10.1	99
Battery storage	MWh	-	-	650

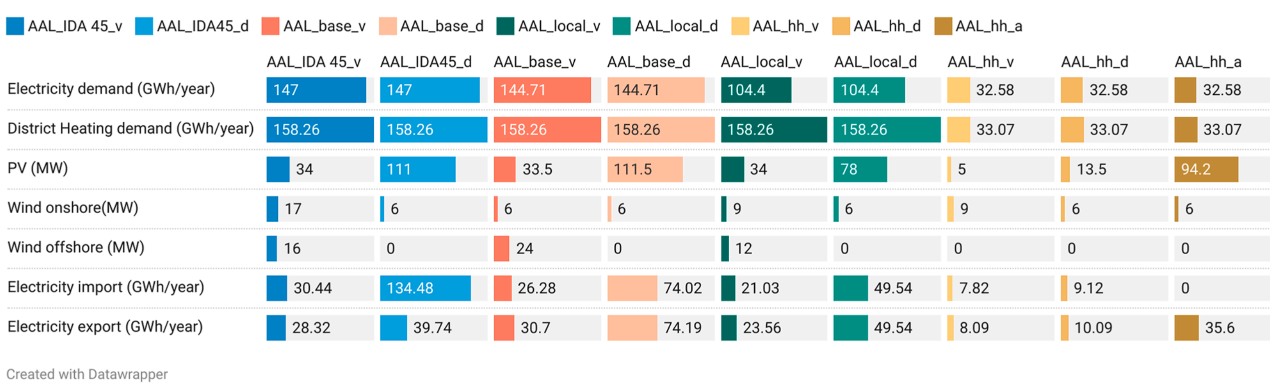

Fig. 8. Overall comparison of all scenarios of Aalborg East as a PED.

included in the system, PED can be realized as PED virtual allowing the use of RES capacities beyond geographical boundaries. PED can also be achieved as dynamic by neglecting industry production, but taking into account public buildings, households and the service sector, and industrial heating needs in the analysis. However, if only the energy use of households at the district level is considered, the PED can be realized as virtual, dynamic or autonomous.

In this regard, Fig. 10 shows the possible coverage of the energy sectors depending on which definition of PED is used.

Although the results of this study pertain to a single district in Denmark, they can serve as a basis for drawing general conclusions applicable to other similar urban areas. When PEDs are considered as tools for reducing CO_2 emissions in cities, it becomes evident that there is no one-size-fits-all solution, as each urban environment possesses its own unique characteristics. However, if PEDs encompass industrial and transport sectors, it can be argued that the temporal energy demand is relatively similar across European countries, and it is likely that the energy demand of a district will exceed its production capacity. As a consequence, in densely populated urban areas, it is unlikely that a PED can achieve its status if it relies solely on energy production within its own boundaries. At the same time, when considering districts with favorable conditions for energy production, such as the potential for installing multiple wind turbines and sufficient rooftop area for PV panels, the issue of fairness in implementing the energy transition arises. Specifically, if such districts exist in countries that also contain densely populated urban districts or areas where grid development is not feasible, can it be considered fair at the national level for certain regions to be deemed more advantageous solely due to their better conditions

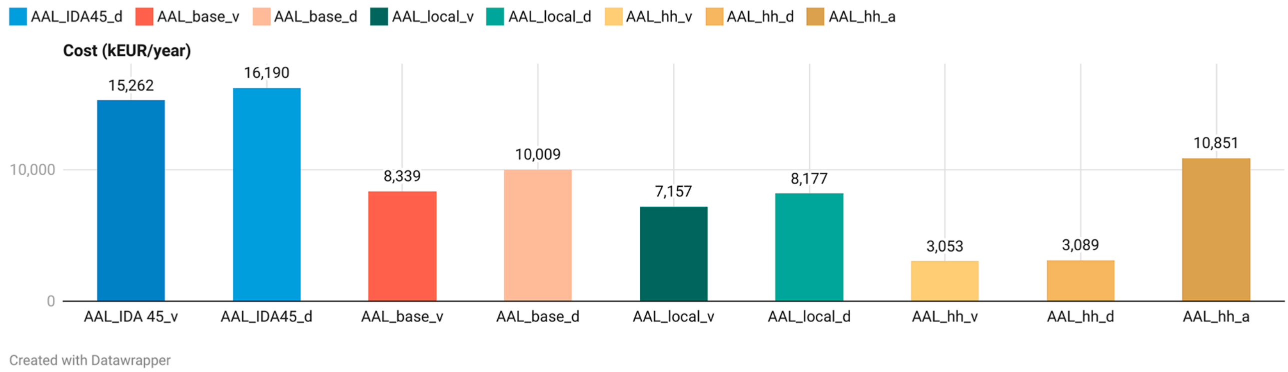

Fig. 9. Overall comparison of the costs of all scenarios of Aalborg East as a PED.

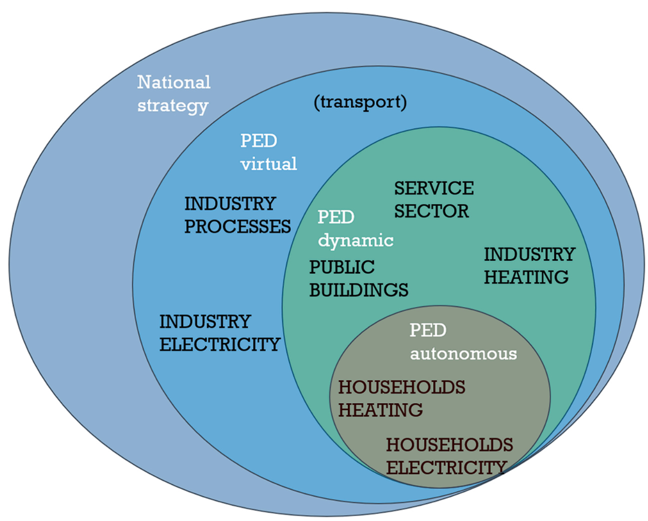

Fig. 10. Different definitions of PEDs and their scopes for the realization of the scenario.

for energy production and alignment with energy demand? In addition, densely populated urban areas often include energy vulnerable households, which must not be overlooked in the process of energy transition. The concept of PED should be accessible to all, in an equitable manner. Accordingly, existing definitions of PEDs can serve as a starting point for achieving climate neutrality in urban environments. However, for PEDs to be feasible at the national level, they must not be oversized but rather defined in accordance with the specific needs and conditions of each district. In this context, it is crucial to establish a network of PEDs that can exchange energy among themselves when energy exchange is mutually beneficial, thereby maximizing their overall efficiency.

Therefore, the pursuit of PEDs should be approached in a manner that is both economically viable and technically feasible. The interpretation of a PED in terms of energy import/export should not be rigidly uniform; rather, it should aim to align with national and global objectives in combating climate change and fostering sustainable urban environments that enhance the quality of life for citizens. This approach is essential for achieving climate neutrality, both in urban areas and across nations.

The results of this study indicate that the realization of PEDs largely depends on the chosen definition. On the one hand, virtual PEDs open up possibilities for innovative solutions that align with national strategies and are more economically viable. On the other hand, autonomous PEDs may lead to the emergence of new challenges and limit the broader applicability of the concept, making its implementation feasible only in specific geographic areas or in regions with lower energy demands. Consequently, the authors proposed a redefinition of a PED: A district can be considered a Positive Energy District if it actively engages in the decarbonization process in alignment with national goals, through continuous improvement of energy efficiency and maximal utilization of waste heat, while utilizing the territorial availability of RES. Simultaneously, a PED is part of the energy network, interconnected with other districts with which it exchanges energy in accordance with the current energy demands of all residents, including energy-poor households.

The findings presented in this study are derived from a case study analysis focused primarily on the energy demand within the PED. While research provides valuable insights into the performance of different PED configurations, it is important to acknowledge that the scope of the study does not encompass the broader implications of PED implementation. In practice, PEDs influence a range of interconnected dimensions, including social, environmental, and economic factors. Therefore, future research should aim to investigate how varying definitions of PEDs affect not only the energy sector, but also the wider systemic impacts within the district. Such an integrated approach would contribute to a more comprehensive understanding of PEDs as complex socio-technical systems.

6. Conclusions

This paper examines the impact of sector integration within a district system on the potential for realizing PED, using Aalborg East as a case study. A comprehensive methodology is introduced, grounded in principles of fairness, which can be applied to various case studies of PEDs. This methodology was specifically implemented within a city district delineated by its postal code.

The results presented underscore the complexity of the concept of PEDs and highlight the need for a clear definition. While a PED virtual offers a pathway to align with national principles, a PED autonomous can only be realized under conditions of limited energy demand. When the analysis of energy districts includes all sectors (industry, transport and buildings), achieving a positive annual energy balance is only feasible if renewable energy is produced outside the district's geographical boundaries. The analysis conducted in the paper demonstrates that the concept of a virtual PED becomes the only realistic option. Conversely, if the industrial and transport sectors are excluded, certain urban areas may be capable of producing sufficient energy to meet household demand, potentially qualifying as autonomous PEDs. However, in northern Denmark, the realization of an autonomous PED is practically unfeasible without resorting to economically unsustainable solutions, such as excessive battery storage. Moreover, the seasonal discrepancy between energy production and demand, particularly the overproduction in summer due to PV reliance, can lead to grid congestion, thereby creating new challenges in the pursuit of decarbonization.

Although being a single case study, the findings contribute to the development of an understanding of the broader context of any PED. Namely, the results highlight that there is no universal solution for PED implementation as urban areas differ significantly in their spatial, infrastructural, and socio-economic characteristics. Therefore, PED strategies need to be adapted to local conditions, with flexible interpretations of energy import/export that align with national and global climate goals. In this context, the establishment of interconnected PED networks capable of exchanging energy is essential for maximizing efficiency and achieving climate neutrality.

Additionally, the fairness of the energy transition must be considered. Districts with favorable conditions for renewable energy production, such as ample space for PV installations or wind turbines, should not be the sole focus of PED development. Densely populated urban areas, often home to energy vulnerable households, must also be included in the transition. PED processes should be accessible and equitable, ensuring that all citizens benefit from sustainable energy solutions.

Ultimately, a district can be considered a Positive Energy District if it actively contributes to national decarbonization goals through enhanced energy efficiency, optimal use of waste heat, and the integration of locally available renewable energy sources. At the same time, it must function as part of a broader energy network, exchanging energy with other districts in response to real-time demand. For PEDs to be viable at the national level, they must be optimally scaled and contextually defined, balancing technical feasibility, economic sustainability, and social equity.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Jelena Nikolic: Writing – original draft, Software, Methodology, Conceptualization. **Jakob Zinck Thellufsen:** Writing – review & editing, Supervision, Resources, Methodology, Data curation. **Peter Sorknæs:** Writing – review & editing, Validation, Investigation, Formal analysis. **Poul Thøis Madsen:** Writing – review & editing, Validation. **Lasse Schytt Nørgaard:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jakob Zinck Thellufsen reports financial support was provided by Innovation Fund Denmark. Peter Sorknaes reports financial support was provided by Innovation Fund Denmark. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2025.106817.

Data availability

Data will be made available on request.

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