Investigating the Role of Geographic Information Systems in Advancing Positive Energy Districts

Ayşenur Koçyiğit[1], Koray Aksu[1], Aydın Furkan Terzi[1,2], Hande Demirel[1]

[1] Department of Geomatics Engineering, Faculty of Civil Engineering, Istanbul Technical University, 34469, Istanbul Türkiye – (kocyigit19, aksuko, terzia18, hande.demirel)@itu.edu.tr
[2] Department of Military Sciences, Turkish Air Force Academy, National Defence University, 34149, Istanbul, Türkiye – aydinfurkan.terzi@msu.edu.tr

Keywords: Geographic Information Systems (GIS), Positive Energy Districts (PED), Renewable Energy, Spatial Analyses, Spatial Data

Abstract

Buildings represent a significant portion of global energy demand, with the European Union accounting for approximately 40% of total energy consumption and 36% of CO_2 emissions. In response to these pressing challenges, the concept of Positive Energy Districts (PEDs) has emerged as a forward-thinking framework. This concept incorporates elements of urban decarbonization and energy sharing mechanisms. The primary objectives of PEDs are to enhance energy efficiency and to advance environmental, social, and economic sustainability within urban settings. Several key projects, including MAKING-CITY, POCITYF, ATELIER, CityxChange, PROPEL, and PED4ALL, are being undertaken to facilitate the large-scale deployment and replication of PEDs.This study aims to examine the definitions and evolving scope of the PED concept, review significant European Union-funded initiatives, and highlight the vital role of Geographic Information Systems (GIS) in the planning and implementation of PEDs. GIS offers robust advantages in the management, analysis, and visualization of spatial data. Furthermore, a comparison of 2D and 3D GIS applications underscores that 3D-GIS enables more detailed and realistic analyses, facilitating accurate evaluations of solar potential, shading effects, and renewable energy capacity at both the building and district levels. The findings indicate that the integration of GIS, particularly through 3D-based analyses, significantly enhances the feasibility, scalability, and decision-making processes associated with PED initiatives.

1. Introduction

Buildings are responsible for a significant portion of global energy demand. In the European Union (EU), they represent the largest consumer sector, accounting for 40% of total energy consumption and 36% of energy-related CO2 emissions (Maestosi, 2021). Cities play a vital role in addressing climate change and have great potential to reduce global emissions. To transition to more sustainable and climate-neutral cities, it is essential to focus on building renovations and the implementation of distributed renewable energy technologies within urban areas (Moreno et al., 2021). In this framework, Nearly Zero Emission Zones (NZED) have been established to promote environmental sustainability and mitigate the impacts of global warming and climate change (Komninos, 2022).

The Positive Energy District (PED) concept builds on the Nearly Zero Emission Buildings (NZEB) framework, which was developed to promote environmental sustainability and mitigate climate change effects. This concept has been enhanced to include elements of urban decarbonization and building energy sharing (Siakas et al., 2025). PEDs aim to improve the quality of life in European cities while enhancing capacity and knowledge, positioning Europe as a global role model for sustainability (Guarino et al., 2023). Moreover, PEDs can provide various benefits, including enhanced urban energy efficiency, promoting sustainable transportation, facilitating digitalization, strengthening the integration of renewable energy sources, alleviating energy poverty, and overall improving sustainability (Sihvonen et al., 2025).

In this context, the European Strategic Energy Technology (SET) Plan aims to plan, disseminate, and establish 100 PEDs by 2025 (SET Plan Action 3.2). Numerous projects have been initiated to align with the targets set by the European Union. Some of these projects have been completed, while others are still underway. Research has shown that the effectiveness and efficiency of PED-focused applications are significantly improved by utilizing advanced technologies such as Geographic Information Systems (GIS).

The primary aim of this study is to provide a thorough examination of the concept of PEDs within the larger context of sustainable urban development and climate neutrality. To achieve this, the research first investigates and critically assesses various definitions of PEDs found in the literature while analyzing the scope and objectives of initiatives and projects aimed at bringing the PED vision to life. By reviewing these initiatives, the study seeks to demonstrate how PEDs have transitioned from theoretical concepts into practical tools that incorporate environmental, social, and economic dimensions of sustainability. Another goal of this study is to evaluate the role of GIS in the planning, implementation, and replication of PEDs. The emphasis is placed on GIS's potential to support spatial data management, advanced spatial analysis, and effective visualization in decision-making processes. This research underscores the complementary roles of two-dimensional (2D) and three-dimensional (3D) GIS applications, emphasizing their distinct advantages. The strengths of 2D GIS lie in its capacity for basic spatial representation, while 3D GIS is particularly effective for realistic modeling of urban layouts, building geometries, and assessing renewable energy potential. By addressing these elements, the study aims not only to illustrate the added value of GIS in enhancing the reliability, feasibility, and scalability of PED methodologies but also to emphasize its significance as a decision-support tool for guiding

https://doi.org/10.5194/isprs-archives-XLVIII-4-W18-2025-221-2026 | © Author(s) 2026. CC BY 4.0 License.

sustainable urban energy transitions and achieving climate-neutral city objectives.

2. PED Concept

2.1 Defintion of PEDs

Within the framework of the PED Programme, a mission-driven, transnational research and development funding programme developed within the framework of the European SET Plan and implemented by JPI Urban Europe, a common reference framework has been established that aims to envision the various dimensions and components of PED implementation. This framework seeks to harmonize different approaches to energy and climate strategies at the city level, taking into account various prerequisites, and aims to develop a unified vision for implementation. The reference framework developed is as follows (JPI Urban Europe):

"*Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups ofconnected buildings which produce net zero greenhouse gas emissions and actively manage anannual local or regional surplus production of renewable energy. They require integration ofdifferent systems and infrastructures and interaction between buildings, the users and theregional energy, mobility and ICT systems, while securing the energy supply and a good life forall in line with social, economic and environmental sustainability.*"

As the scholarship surrounding Positive Energy Districts (PED) continues to evolve, various definitions have been proposed, each offering a nuanced perspective on the concept. Sessa et al. (2025) articulate that a PED consists of urban areas or clusters of interconnected buildings characterized by the absence of greenhouse gas emissions, the incorporation of energy-efficient and resilient designs, and the capacity to manage surplus annual renewable energy production effectively. Similarly, Marrasso et al. (2024) define a PED as a mixed-use, energy-efficient urban environment that achieves net-zero CO_2 emissions. These areas require synergistic interactions among buildings, stakeholders, and regional energy, transportation, and information-communication technology systems, while simultaneously upholding principles of social, economic, and environmental sustainability.

Bruck et al. (2022) further contribute to the discourse by defining a PED as urban regions wherein local renewable energy production surpasses energy consumption from external sources, thereby achieving a net-zero carbon emission balance. Ding and Gou (2025) characterize a PED as an urban zone that realizes an annual net positive energy balance, which encompasses the utilization of renewable energy sources, enhancements in energy production efficiency, and active community participation in energy management initiatives. Finally, Gouveia et al. (2021) present a definition of a PED as an urban area distinguished by its highly energy-efficient and adaptable structures, characterized by net-zero energy imports and greenhouse gas emissions, and oriented towards the production of a substantial surplus of local renewable energy on an annual basis.

An examination of various definitions in the literature reveals that the concept of a PED is centered around urban areas or interconnected clusters of buildings that do not produce greenhouse gas emissions. These districts demonstrate high energy efficiency and flexibility, with the goal of maintaining local renewable energy production that exceeds consumption. All definitions share the common objective of achieving a net-zero carbon emission balance while effectively managing annual renewable energy surpluses. Additionally, they emphasize the importance of integration and interaction among buildings, users, and regional systems related to energy, transportation, and information and communication technologies. Some definitions explicitly include dimensions of social, economic, and environmental sustainability, while others focus more on the physical energy balance, the relationship between production and consumption, and technical parameters within regional boundaries. In this context, the PED concept is viewed as an interdisciplinary and holistic approach to smart cities, encompassing not only technical energy performance but also social and environmental aspects.

2.2 PED Projects

In alignment with the sustainability and decarbonization objectives of the European Union, the development and enhancement of urban areas characterized by high energy efficiency, significant renewable energy production capacity, and the attainment of net-zero greenhouse gas emissions are being pursued. A range of PED projects is being supported for implementation across various scales and diverse socio-technical contexts. Notable examples of these projects include PROPEL, MAKING-CITY, POCITYF, ATELIER, CityxChange, and PED4ALL.

The Positive Robust PED Localities (PROPEL) project is supported by the Positive Energy Districts and Neighbourhoods (ENPED) program, a key initiative backed by JPI Urban Europe. The project aims to enhance the resilience and viability of regions by integrating innovative energy components, thereby improving their capacity for off-grid operations. Additionally, PROPEL seeks to expand the boundaries of PEDs by incorporating transportation and biogas systems (PROPEL) The MAKING-CITY project focuses on designing regional energy plans and PEDs using a bottom-up approach. It emphasizes the development of robust urban visions and promotes knowledge sharing to encourage greater citizen participation. This project systematically employs GIS-based spatial analysis to enhance the effectiveness of planning and implementation processes (MAKING CITY). The POCITYF project focuses on developing integrated and innovative solutions to accelerate the energy transition and support the creation of PEDs. It aims to bring together technology providers, local governments, and citizens. This initiative involves testing and implementing various mechanisms in pilot projects across select regions, including peer-to-peer (P2P) energy trading, token-based systems that reward sustainable behavior, and digital platforms designed to enhance citizen participation (POCITYF). The ATELIER project seeks to facilitate the sharing, distribution, and trading of renewable energy among individuals and institutions, emphasizing on establishing smart grids within a community-based framework (ATELIER). Similarly, the CityxChange project is dedicated to transforming regions into Positive Energy Blocks (PEBs). It accomplishes this by developing a comprehensive set of tools for managing local energy systems. These tools provide data on grid topology, generate demand and generation forecasts, and analyze the impact of local energy resources on overall system performance (Dahlen et al. 2020). In conclusion, the PED4ALL project views PEDs as a means to transform energy production, distribution, and consumption. The goal is to achieve improvements at the neighborhood level and contribute to decarbonization. The project aims to integrate technical, economic, social, and spatial knowledge, as well as contributions from energy system stakeholders, leveraging a co-creation process to combine the best elements from each project phase (PED4ALL).

The projects presented illustrate that the PED approach is being implemented across various scales, technological infrastructures, and socio-technical contexts, aligning with the European Union's sustainability and decarbonization goals. Initiatives such as PROPEL, MAKING-CITY, POCITYF, ATELIER, CityxChange, and PED4ALL address the PED concept not only regarding technical energy performance but also as a comprehensive tool for transformation that includes social, economic, and environmental dimensions.

These projects aim to enhance the effectiveness of PED implementations through diverse methods, such as diversifying renewable energy production and management models, utilizing smart grids and GIS-based planning tools, increasing citizen participation, and developing local energy trading and reward mechanisms. By piloting these initiatives in various countries and contexts, they contribute to strengthening the technical resilience and applicability of PEDs, facilitating greater integration of energy systems with transportation, information and communication technologies, and urban infrastructures. In conclusion, PED projects play a crucial role in accelerating the energy transition at both local and regional levels, significantly contributing to the achievement of long-term climate neutrality goals.

3. PED and GIS

GIS is a technology that allows users to create, manage, analyze, and visualize different types of data on maps (ESRI). GIS provides several advantages in collecting, managing, and storing information (Wang et al., 2021). Additionally, the integration of GIS with Multi-Criteria Decision Making (MCDM) methods streamlines the decision-making process, which is why they are often used together (Vavatsikos et al., 2019).

When developing the concept of PEDs, it is essential to consider all environmental, social, and economic dimensions. To effectively manage this multidimensional approach, decision-makers need tools that facilitate multi-stakeholder assessments through Multi-Criteria Decision Analysis (MCDA) methods. In this context, GIS plays a crucial role by analyzing and visualizing spatial data. This ensures that the information generated is presented in an understandable format that can be easily shared with all stakeholders (Bisello et al., 2023). GIS provides a strong foundation for addressing challenges related to spatial data management and supports the effective visualization of PEDs (Alpagut et al., 2021). Thanks to its capabilities in spatial data management and analysis, GIS methodologies are adaptable and replicable across various urban contexts, enhancing the applicability of PEDs (Sessa et al., 2025).

GIS is a valuable tool that allows for the representation and analysis of georeferenced data, facilitating the examination of spatial development and the temporal dynamics of transformation processes. It enables the graphical visualization of the outcomes of suitability analyses (Bisello et al., 2023). Suitability maps created as part of the MAKING-CITY project are displayed in Figure 1. The figure shows PED suitability maps produced for six different cities as a result of spatial analyses, and the most suitable areas for PED establishment in the cities are colored blue, while the least suitable areas are colored red.

Apart from the preparation of suitability maps, GIS is also used in different studies, such as creating simulation models based on cadastral GIS data of cities to calculate energy demand for the development of the PED concept and performing solar energy analyses with PVGIS software (Alpagut et al., 2019; Gouveia et al., 2021).

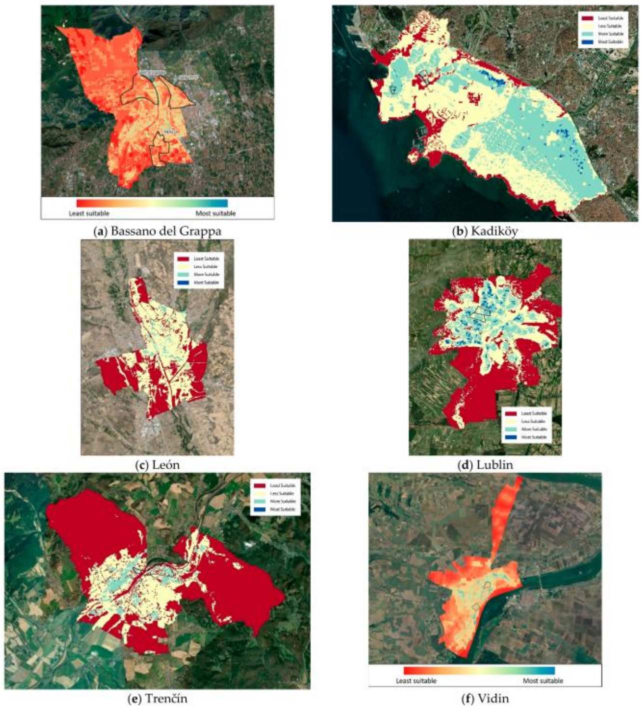


Figure 1. Suitability maps from MAKING-CITY project (Alpagut et al., 2021).

In conclusion, GIS are essential tools that aid in decision-making processes through effective spatial data management, analysis, and visualization in the development of PED concepts. Applications like the creation of suitability maps, energy demand simulations, and solar energy potential analyses showcase the versatile functionality of GIS. This versatility enhances the adaptability and replicability of methodologies across various urban contexts, ultimately strengthening the implementation of PEDs.

3.1 Impact of 2D-GIS and 3D-GIS to PED

GIS plays a vital role in the development, implementation, and dissemination of the concept of PED. In this context, both 2D and 3D analyses are essential, with 3D-GIS offering significant advantages over 2D-GIS due to its advanced features.

While 2D-GIS provides a flat representation of spatial data and is useful for basic analyses, it has limitations when it comes to complex urban structures. For example, Figure 2 indicates a map created with 2D data, illustrating the spatial distribution of the average CO2 column concentration (XCO2). In contrast, 3D-GIS delivers a more detailed and realistic spatial representation. The use of 3D visualization allows for a more intuitive perception of terrain and its structures. Additionally, 3D-GIS facilitates more accurate terrain-based route planning and resource management. Thus, although 2D-GIS is important for fundamental spatial analysis, 3D-GIS provides more advanced capabilities and crucial support for decision-making (Li, 2025).

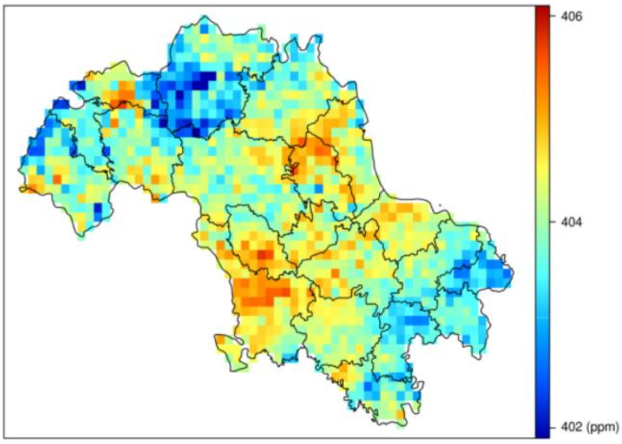
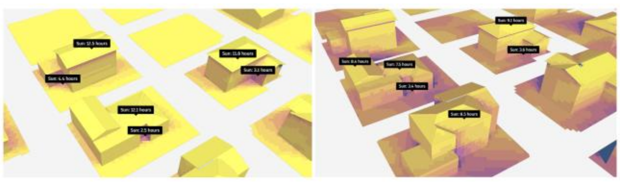


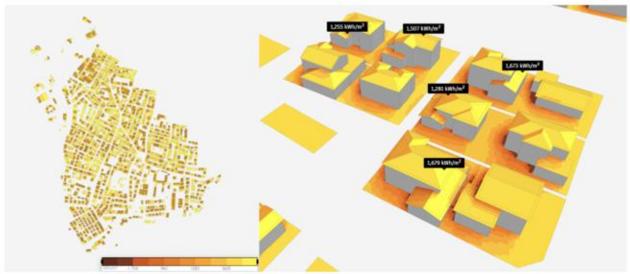
Figure 2**.** An example of a map produced with 2D data (Yang et al., 2025)

The real world is a complex structure made up of 3D objects. In this context, 3D-GIS enables a more intuitive, comprehensive, and realistic understanding of geographic features and spatial data. This enhanced visualization helps users better comprehend the geographic environment and associated resources, significantly improving management processes and business efficiency (Q. Wang & Li, 2022).

When evaluated from the perspective of the PED concept, 3D-GIS provides detailed analyses that enhance our understanding of PEDs. Through 3D spatial analyses such as sun hours, shadow changes, solar potential, and wind analysis, researchers can more effectively assess the renewable energy potential of PEDs. Including building facades in these analyses yields even more comprehensive results. 3D analyses allow for more accurate determination of potential energy production areas or the most suitable PED areas within PED areas (Demirel et al., 2025). The results of two important 3D analyses for PED studies, sun hours (a) and solar potential (b), are illustrated in Figure 3. A closer look at the figure shows that, unlike traditional 2D analyses, 3D analyses can evaluate solar potential on both building facades and roofs. Thus, not only building locations but also the geometric characteristics of roofs and facades can be included in the analysis, increasing the accuracy of solar potential calculations. Therefore, 3D-GIS applications contribute to a more realistic and reliable determination of renewable energy potential.



(a) Sun hour analysis



(b) Solar potential analysis

Figure 3. Results of some of the 3D analyses (Demirel et al., 2025).

In conclusion, both 2D and 3D GIS applications play complementary roles in the development of the PED concept. However, 3D-GIS significantly enhances this process by offering more detailed and realistic analysis capabilities. While 2D-GIS is essential for managing and visualizing basic spatial data, 3D-GIS enables a more thorough analysis of various parameters, including renewable energy potential, sunshine duration, shade variations, and wind effects. By incorporating spatial information along with detailed roof and façade geometries, 3D-GIS produces more accurate and reliable results. Consequently, these advantages of 3D-GIS offer dependable decision support for selecting PED areas, evaluating energy production potential, and aiding sustainable urban planning processes.

Conclusion

This study offers a comprehensive assessment of the PED concept by exploring its foundational principles, definitions in the literature, objectives set by the European Union, and examples of projects that have been implemented. It specifically analyzes the PROPEL, MAKING-CITY, POCITYF, ATELIER, CityxChange, and PED4ALL projects, outlining their strategies for implementing PEDs across various scales and contexts. The primary goal of the PED concept is to develop urban areas that are highly energy-efficient, resilient, and free of greenhouse gas emissions, while also effectively managing annual surplus renewable energy production.

The literature review indicates that PEDs are not solely focused on technical and physical energy balance; instead, they serve as a holistic transformation tool that encompasses social, economic, and environmental sustainability dimensions. In this context, the PED concept is vital for the decarbonization of European cities, fostering the development of energy-sharing mechanisms and enhancing citizen participation.

Additionally, the study examines the integration of GIS with the PED concept. The capabilities of GIS in spatial data management, analysis, and visualization provide effective decision support for stakeholders involved in multi-stakeholder processes, thereby increasing the adaptability of PED applications in diverse urban contexts. A comparative evaluation of 2D and 3D GIS analyses reveals that 3D-GIS yields more accurate and reliable results in areas such as energy potential analysis, sunshine duration, shade variations, and wind modeling. Consequently, 3D-GIS is recognized as a dependable tool for identifying PED areas, calculating energy production potential, and supporting sustainable urban planning processes.

The analysis demonstrates that the widespread use of GIS-based evaluations, particularly the integration of 3D spatial modeling techniques, is essential for the successful implementation of the PED concept. It is expected that this approach will significantly contribute to the creation of climate-neutral cities by accelerating urban energy transformation in line with the European Union's 2025 goals.

Acknowledgment

This work was carried out within the framework of the PROPEL project (Project number 43786223) and was supported by the European Union's JPI Urban Europe PED programme.

This work was supported by the Scientific and Technological Research Council of Türkiye (Positive Robust PED Localities) under Project 122N696.

This study does not reflect the ideas of Ministry of the National Defense of Republic of Türkiye.

References

Alpagut B, Akyürek Ö, Mitre EM: Positive Energy Districts methodology and its replication potential. Proceedings. 2019; 20(1): 8.

Alpagut, B., Romo, A. L., Hernández, P., Tabanoğlu, O., & Martinez, N. H. (2021). A GIS-Based Multicriteria Assessment for identification of positive Energy Districts boundary in cities. *Energies, 14*(22), 7517. https://doi.org/10.3390/en14227517

ATELIER. (2024). AmsTErdam BiLbao cItizen drivEn smaRt cities. https://smartcity-atelier.eu/;

Bisello A, Bottero M, Volpatti M, et al.: Multicriteria Spatial Economic Decision support Systems to support Positive Energy Districts: A literature review. Green Energy and Technology. 2023; 15–31.

Bruck, A., Ruano, S. D., & Auer, H. (2022). One piece of the puzzle towards 100 Positive Energy Districts (PEDs) across Europe by 2025: An open-source approach to unveil favourable locations of PV-based PEDs from a techno-economic perspective. *Energy, 254*, 124152. https://doi.org/10.1016/j.energy.2022.124152

Dahlen KE, Purshouse N, Antolic M: D2. 2 Toolbox for design of PEB including e-mobility and distributed energy resources. 2020.

Demirel, H., Koçyiğit, A., Alpagut, B., & Muhcu, D. (2025). Evaluating the solar energy potential for Positive Energy Districts (PED) through advanced 3D Geographic Information System (GIS) analysis. *Open Research Europe, 5*, 81. https://doi.org/10.12688/openreseurope.19075.2

Ding, L., & Gou, Z. (2025). Designing Energy-Resilient Communities: A School-Centric Approach to Positive Energy Districts with Integrated Storage System. *Renewable Energy*, 123785. https://doi.org/10.1016/j.renene.2025.123785

ESRI. (n.d.). What is GIS. https://www.esri.com/en-us/what-is-gis/overview

Gouveia, J. P., Seixas, J., Palma, P., Duarte, H., Luz, H., & Cavadini, G. B. (2021). Positive Energy District: A model for historic districts to address energy poverty. *Frontiers in Sustainable Cities, 3*. https://doi.org/10.3389/frsc.2021.648473

Guarino, F., Rincione, R., Mateu, C., Teixidó, M., Cabeza, L. F., & Cellura, M. (2023). Renovation assessment of building districts: Case studies and implications to the positive energy districts definition. *Energy and Buildings, 296*, 113414. https://doi.org/10.1016/j.enbuild.2023.113414

JPI Urban Europe / SET Plan Action 3.2 (2020). White Paper on PED Reference Framework for PositiveEnergy Districts and Neighbourhoods. https://jpi-urbaneurope.eu/ped/

Komninos, N. (2022). Net Zero Energy Districts: Connected intelligence for Carbon-Neutral Cities. *Land, 11*(2), 210. https://doi.org/10.3390/land11020210

Li, Y. (2025). Research on earthquake simulation system based on 3D GIS technology. *International Journal of High Speed Electronics and Systems*. https://doi.org/10.1142/s0129156425408083

Maestosi, P. C. (2021). Smart Cities and Positive Energy Districts: Urban Perspectives in 2020. *Energies, 14*(9), 2351. https://doi.org/10.3390/en14092351

MAKING-CITY. (2019). Making City. https://makingcity.eu/

Marrasso, E., Martone, C., Pallotta, G., Roselli, C., & Sasso, M. (2024). A novel methodology and a tool for supporting the transition of districts and communities in positive energy districts. *Energy and Buildings, 318*, 114435. https://doi.org/10.1016/j.enbuild.2024.114435

Moreno, A. G., Vélez, F., Alpagut, B., Hernández, P., & Montalvillo, C. S. (2021). How to Achieve Positive Energy Districts for Sustainable Cities: A proposed calculation Methodology. *Sustainability, 13*(2), 710. https://doi.org/10.3390/su13020710

PED4ALL. (2023). Positive Energy Distircts For All. https://ped4all.eu/discover/

POCITYF. (n.d.). POCITYF. https://pocityf.eu/

PROPEL. (n.d.). Positive RObust PEd Localities. https://sites.google.com/view/propel-ped/home-page

Sessa, E., Brunetti, A., Ciulla, G., Guarino, F., Longo, S., Cellura, M., Dragomir, A., & Papina, C. (2025). Towards Positive Energy District Assessment: The Case Study of Bucharest. *Energy*, 136208. https://doi.org/10.1016/j.energy.2025.136208

SET Plan Action 3.2. (2018). Europe to become a global role model in integrated, innovative solutions for the planning, deployment, and replication of Positive Energy Districts. https://jpi-urbaneurope.eu/wp-content/uploads/2021/10/setplan_smartcities_implementationplan-2.pdf

Siakas, D., Rahanu, H., Georgiadou, E., Siakas, K., & Lampropoulos, G. (2025). Positive energy districts enabling smart energy communities. *Energies, 18*(12), 3131. https://doi.org/10.3390/en18123131

Sihvonen, V., Annala, S., & Koljonen, O. (2025, May). A review of Positive Energy Districts' goals and services: Insights for business model design. In *Proceedings of the 21st International Conference on the European Energy Market (EEM)* (pp. 1–8). IEEE. https://doi.org/10.1109/EEM64765.2025.11050231

Vavatsikos, A. P., Demesouka, O. E., & Anagnostopoulos, K. P. (2019). GIS-based suitability analysis using fuzzy PROMETHEE. *Journal of Environmental Planning and Management, 63*(4), 604–628. https://doi.org/10.1080/09640568.2019.1599830

Yang, K., Zou, R., Zhang, W., Zeng, X., Li, Z., & Guo, J. (2025). Comprehensive review of Positive Energy Districts: Multidimensional analysis of energy, economic, social, and environmental aspects. *Renewable and Sustainable Energy Reviews, 217*, 115740. https://doi.org/10.1016/j.rser.2025.115740

Wang, Q., & Li, Y. (2022). Research on simulation of distribution network engineering scene based on 3D GIS technology. *Wireless Communications and Mobile Computing, 2022*, 1–9. https://doi.org/10.1155/2022/7736655

Wang, S., Zhang, F., & Qin, T. (2021). Research on the construction of highway traffic Digital twin System based on 3D GIS technology. *Journal of Physics Conference Series, 1802*(4), 042045. https://doi.org/10.1088/1742-6596/1802/4/042045