Mapping Positive Energy: A Geographic Information System Approach to Defining Positive Energy Districts

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Abstract
Positive Energy Districts (PEDs) are urban areas strategically designed to reduce climate impact and promote sustainability by maximizing renewable energy use and optimizing energy consumption. Aligned with the European Strategic Energy Technology (SET) Plan, the aim is to establish 100 PEDs by 2025. This study utilized the Best-Worst Method (BWM) from Multi-Criteria Decision-Making (MCDM) techniques to assess criteria influencing PED boundaries. It also evaluated the effects of two-dimensional (2D) and three-dimensional (3D) data analyses on these boundaries. The findings suggest that combining 2D and 3D data yields more comprehensive results, with 3D data enhancing assessments of solar and wind energy. Regions with access to clean energy and favorable climate are ideal for PEDs, particularly where socio-economic status and education levels are high.

1. Introduction

Positive Energy Districts (PEDs) are urban areas designed to minimize climate impact and promote sustainability by maximizing the use of renewable energy sources and optimizing energy consumption (RISE, 2025). The concept of PEDs emerged to facilitate the energy transition and contribute to climate neutrality through enhanced energy efficiency and achieving a net-zero energy balance (Derkenbaeva et al., 2021). After extensive discussions with stakeholders, including cities and urban actors, the PED Programme developed a Reference Framework. According to this framework," Positive Energy Districts are energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability." (JPI Urban Europe, 2025).

The action plan titled "Smart Cities and Communities" developed as part of the European Strategic Energy Technology (SET) Plan, aims to facilitate the planning, establishment, and replication of 100 PEDs for sustainable urbanization by 2025 (SET Plan Action 3.2). In this context, several European Union-supported projects, such as MAKING-CITY, CitxChange, POCITYF, and PED4ALL, have played a significant role in achieving this goal. This study is also conducted under the PROPEL project, which is one of the initiatives supported by the European Union (MAKING-CITY, 2025; CityxChange,2025; POCITYF,2025; PED4ALL, 2025; PROPEL, 2025).

Significant distinctions exist among regions concerning their renewable energy landscapes, encompassing factors such as the availability of renewable energy sources, energy storage potential, population demographics, energy consumption patterns, costs, and regulatory frameworks. These elements collectively influence the design and operation of PEDs, resulting in unique characteristics for each district (Lindholm et al., 2021). In the process of identifying suitable areas for PEDs, a comprehensive analysis is conducted that considers various critical factors. These factors include the potential for solar energy, the options for district heating and cooling, the availability of wind and geothermal energy, and the density of the population in the region. Additionally, the local context regarding renewable energy source potential and the geographic location, along with related mobility considerations, are essential. Future environmental projections, particularly regarding carbon-free energy demand and supply, are also evaluated. Furthermore, financial assessments, renewal strategies, dynamics within energy communities, welfare and security implications, and marketing considerations play crucial roles in this planning process (Civiero et al., 2021; Zhang et al., 2021; Schneider et al., 2023). Research aimed at determining optimal PED locations often employs a flexible, Geographic Information Systems (GIS) - based Multi-Criteria Decision Analysis (MCDA) approach. This methodology is effective in identifying the most suitable areas for achieving an annual positive non-renewable energy balance. MCDA is instrumental in emphasizing the critical criteria influencing potential locations for positive energy outcomes, while GIS enhances the accuracy and comprehensiveness of the results obtained (Alpagut et al., 2021).

This study aimed to identify the criteria that influence the boundaries of the PED and to establish their respective weights and importance rankings utilizing the Best-Worst Method (BWM), a Multi-Criteria Decision Making (MCDM) approach. The contributions of both two-dimensional (2D) and three-dimensional (3D) data and analyses to the mapping of the PED boundaries were examined through comprehensive analyses. The novelty of this study is derived from a comparative assessment of results obtained through both 2D and 3D analyses. Additionally, it includes a comprehensive 3D evaluation of the potential of renewable energy sources about PED. The findings were assessed from both environmental and social perspectives, resulting in the successful conclusion of the study.

2. Data and Methodology

2.1 Study area

This study focuses on the Kadıköy district of İstanbul, Türkiye, as illustrated in Figure 1. Kadıköy is recognized as one of the most developed districts situated on the Anatolian side of Istanbul, alongside the coast of the Marmara Sea. It encompasses a land area of 25.20 km² and, according to TURKSTAT data for 2024, has a population of approximately 462,189 with estimates suggesting it is nearing half a million residents (Kadıköy Municipality, 2025; TURKSTAT, 2025). The district is known for its high socio-economic status and is primarily composed of residential and commercial areas. It features numerous older buildings that are currently being transformed through urban development. With its cosmopolitan atmosphere and strategically central location, Kadıköy provides a vibrant environment that blends historical and contemporary architecture, appealing to both local and international residents. Kadıköy offers a wide variety of urban activities, including social, cultural, and sporting events, as well as facilities for entertainment, recreation, and shopping. Additionally, it serves as a key transportation hub, featuring seven Marmaray train stations, five metro stations, tram and bus stops, and a ferry terminal. Together, these attributes contribute to a significant daily influx of visitors to the district.

Figure 1. Kadıköy District.

2.2 System Architecture

The system architecture of the study is presented in Figure 2. This methodology encompasses four stages: determining criteria for ped boundaries and calculating weights of criteria, 2D data for mapping PED, 3D data for mapping PED, and evaluating results.

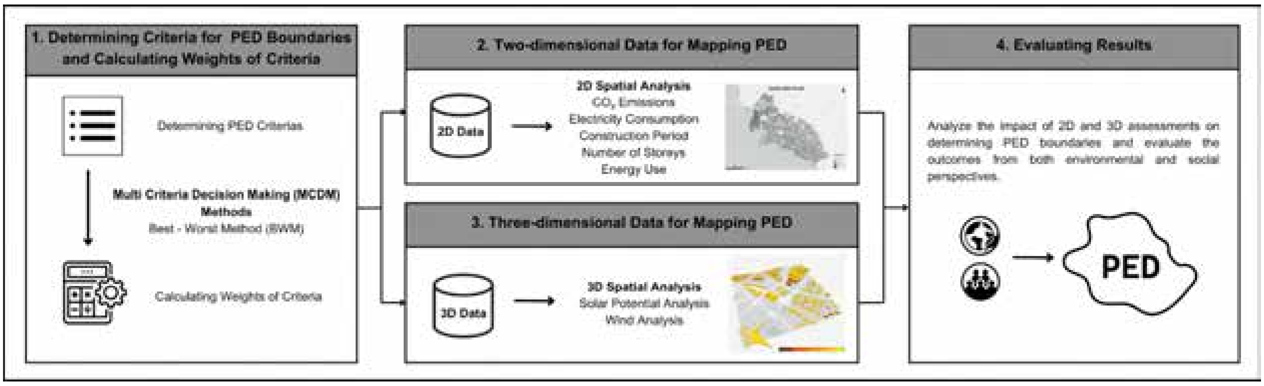


Figure 2. The proposed framework.

This study initially identified the criteria that are essential for establishing the boundaries of PEDs. A thorough review of the literature was conducted to ascertain these criteria, focusing on sources related to PED, sources associated with Zero Emission Districts (ZED) that contributed to the evolution of the PED concept, and relevant projects such as MAKING-CITY and CityxChange (MAKING-CITY, 2025; CityxChange,2025). Subsequent to the identification of the criteria, BWM, the well-known MCDM technique, were applied to evaluate the influence of the criteria and to calculate weights accordingly. After calculating the weights, analyses utilizing both 2D and 3D data were performed to determine the appropriate boundaries for PEDs. These analyses facilitated an evaluation of the advantages provided by both types of data. Open-source data, along with information from the European Union-funded MAKING-CITY and PROPEL projects, were employed in this investigation (MAKING-CITY, 2025; PROPEL, 2025). Data encompassing electricity consumption, greenhouse gas (GHG) emissions, energy types of buildings, and the structural characteristics of these buildings were sourced from these projects. Additionally, socioeconomic data and educational attainment information were obtained from the National Smart City Open Data Platform (Ulusal Akıllı Şehir Açık Veri Platformu -ULASAV) (ULASAV,2025). For the 3D analysis component, a building model was generated based on 2D data of buildings in Kadıköy. Ultimately, the study evaluated potential PED areas in the Kadıköy district, integrating various criteria alongside environmental and social factors.

2.2.1 Determining Criteria for PED Boundaries Calculating Weights of Criteria

As part of this study, a comprehensive literature review was conducted to identify the factors influencing the boundaries of PEDs. This review encompassed an analysis of existing research on the PED concept, as well as the foundational ZED concept. Furthermore, it included an examination of notable projects such as MAKING-CITY and CitxChange (MAKING-CITY, 2025; CityxChange,2025). The findings related to the criteria that affect the boundaries of the PED are presented in Table 1.

Table 1. Criteria about PED boundaries.

Main Criteria	Sub-Criteria
Energy	Biomass
	Natural gas
	Electricity consumption
	Solar energy
	Wind energy
Environment and construction profile	Greenhouse gas emissions (GHG)
	Building density
	Construction period
	Number of storeys
Social	Education level
	Socioeconomic status
	Population

After establishing the decision criteria, the weights for the sub-criteria outlined in Table 1 were computed using the BWM within the context of MCDM. Developed by Jafar Rezaei in 2015, the BWM is a systematic approach that employs two vectors of pairwise comparisons to determine the weights of the criteria (Rezaei, 2015). This method involves identifying the decision criteria, as well as the best and worst criteria. It requires the evaluation of the preference of the best criterion over all other criteria using a numerical scale ranging from 1 to 9, followed by an assessment of how each criterion is preferred over the worst criterion, utilizing the same scale. Finally, the optimal weights are calculated based on these evaluations (Rezaei, 2014).

2.2.2 Two-Dimensional Data for Mapping PED

A multitude of criteria significantly influences the establishment of PED boundaries. MCDM methods are employed to ascertain the relative importance of these criteria. Through the application of MCDM approaches, the impact of each criterion on the decision-making process can be quantitatively assessed and appropriately weighted. Subsequent to these analyses, GIS are employed to spatially evaluate the identified criteria, thereby facilitating the determination of PED boundaries. In addition to providing geographical data pertinent to urban environments, GIS provides essential spatial analysis functions critical to urban design processes (Xia et al., 2022). Moreover, GIS enables the integration of geographical and attribute data with spatial analysis tools and modeling methods, allowing for comprehensive analyses and visualizations of geographical, environmental, and natural resources, thereby supporting quantitative assessments of urban structures (Xia et al., 2022; Wu et al., 2017). Information about the data used in 2D analyses, including data types and sources, is presented in Table 2.

Table 2. Data used for 2D analysis.

Data	Type	Source
Biomass	Vector	PROPEL Project
Natural gas	Vector	PROPEL Project
Electricity consumption	Vector	PROPEL Project
Greenhouse gas (GHG) emissions	Vector	PROPEL Project
Building density	Vector	Derived from PROPEL Project
Construction period	Vector	PROPEL Project
Number of storeys	Vector	PROPEL Project
Education level	Raster	ULASAV

Socioeconomic status	Tabular Data	ULASAV
Population	Vector	TURKSTAT

2.2.3 Three-Dimensional Data for Mapping PED

Another important factors in determining the boundaries of a PED is the potential for solar and wind energy. Solar energy is beneficial for residential areas due to its practicality and cost-effectiveness. 3D spatial analyses can be performed to evaluate these factors in the context of a PED. For this purpose, a 3D building model of the study area was created using existing 2D spatial data. After this model was created, solar energy potential and wind energy analyses were performed using Autodesk Forma with a student license, and solar energy analysis was performed using the open-source Ladybug Tools.

2.2.4 Evaluating Results

In this study, the BWM was employed to identify suitable areas for PEDs. The evaluation criteria were established through a literature review and were organized to encompass environmental, structural, and social dimensions. Criterion weights were calculated using the BWM method to assess the importance of each criterion. Moreover, data related to renewable energy sources, including sun hour, solar energy potential, and wind potential, were analyzed as part of the environmental suitability assessments. Indicators related to biomass and natural gas usage were also examined to identify regions with the capacity to utilize clean energy sources. Social indicators, such as socioeconomic status and educational levels, were incorporated into the analysis due to their connection with technological adaptation and sustainability awareness. All criteria were spatially integrated using GIS-based datasets to create a comprehensive evaluation framework for the applicability of PEDs.

3. Results and Discussion

3.2.1 Determining Criteria for PED Boundaries Calculating Weights of Criteria

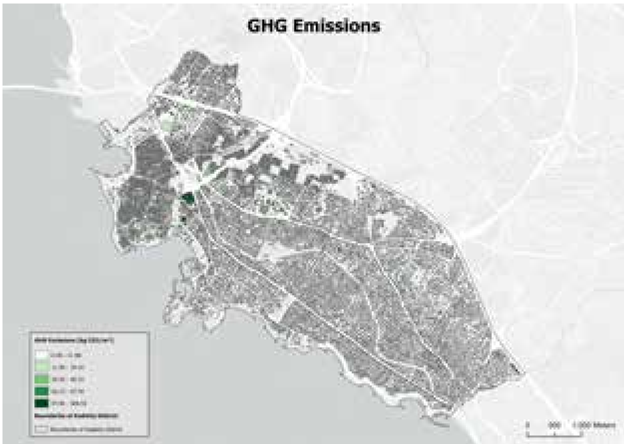
In the context of this study, the weights assigned to the criteria were computed utilizing the BWM, an approach within the realm of MCDM methodologies. This process was undertaken to ascertain the significance levels of the criteria presented in Table 1, which were established through an extensive review of the existing literature. The weights of the criteria derived from the application of the BWM are presented in Table 3.

Table 3. Weights of criteria calculating using BWM.

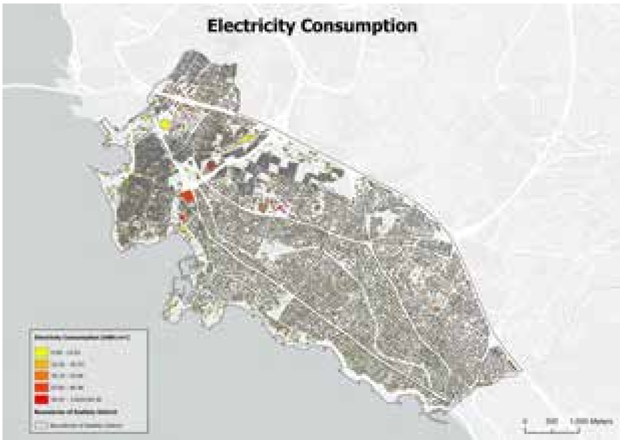
Main Criteria	Sub-Criteria	Weight
Energy	Biomass	0.086
	Natural gas	0.072
	Electricity consumption	0.335
	Solar energy	0.108
	Wind energy	0.034
Environment and construction profile	Greenhouse gas (GHG) emissions	0.174
	Building density	0.041
	Construction period	0.034
	Number of storeys	0.024
Social	Education level	0.011
	Socioeconomic status	0.032
	Population	0.048

3.2.2 Two-Dimensional Data for Mapping PED

As part of the study, both 2D and 3D spatial analyses were conducted to assess the criteria detailed in Table 1. The 2D spatial analyses examined several factors within the Kadıköy district, including GHG emissions (a), electricity consumption in buildings (b), the utilization of biomass and natural gas as energy sources (c and d), the socioeconomic score (e), education levels (f), the year of construction of buildings (g), the number of floors in buildings (h), building density throughout the district (i), and population (j). The maps generated as a result of these spatial analyses are indicated in Figure 3.



(a)



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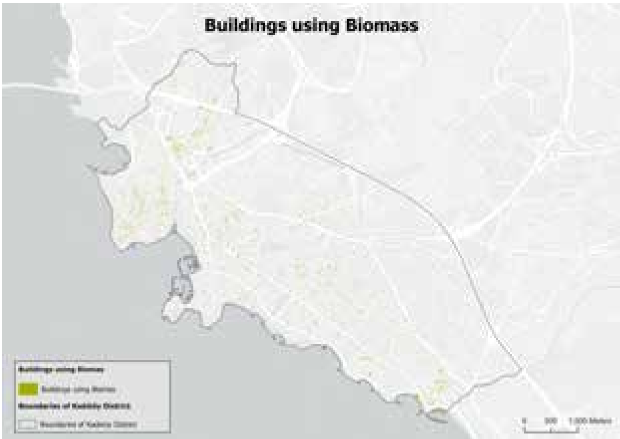
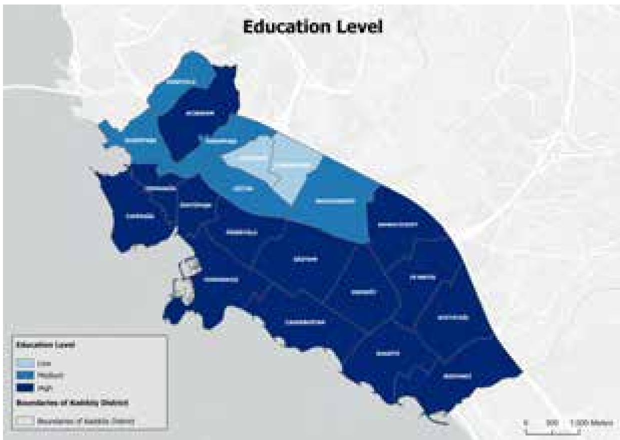


(c)

(d)

(e)



(f)

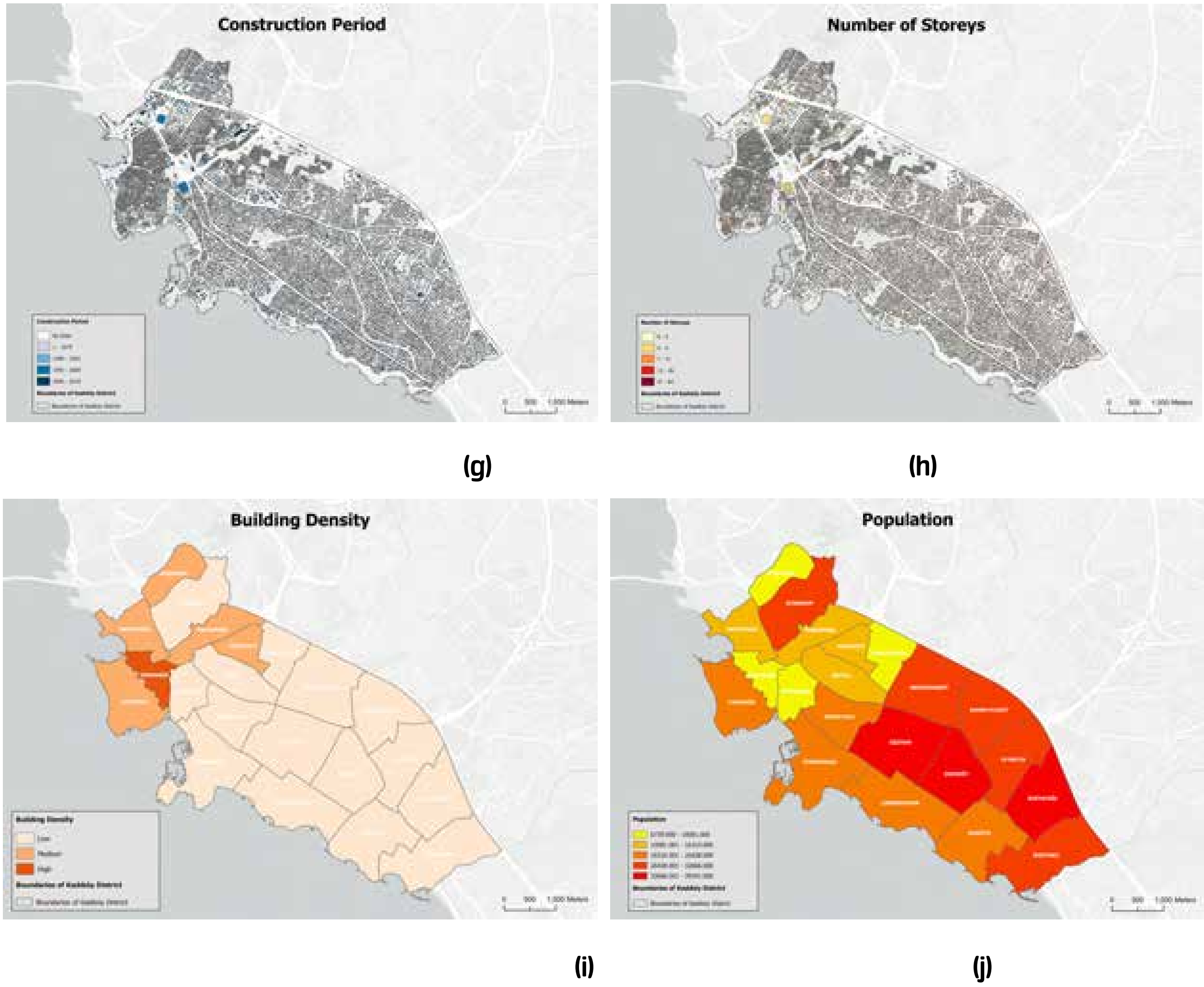


Figure 3. Results of 2D spatial analyses.

Following the creation of criterion maps through 2D spatial analyses, an examination was conducted on the effects of these criteria. The evaluation of the criteria weights presented in Table 3 indicates that the most significant criteria are electricity consumption and GHG emissions. The PED concept aligns with smart city initiatives that aim to reduce energy use and GHG emissions (JPI Urban Europe, 2025). Therefore, an analysis of the 2D spatial results depicted in Figure 3 reveals that regions characterized by low electricity consumption and GHG emissions are conducive to the designation of PEDs.

However, it is essential to recognize that the determination of PED boundaries should not be limited to these two criteria; a comprehensive assessment of additional factors is necessary. While PEDs derive benefits from energy-efficient buildings, smart grids, and advanced renewable energy technologies, they concurrently enhance urban resilience and make substantial contributions to achieving net-zero carbon targets (Bruckner et al., 2025). In this context, factors such as the age of construction and the number of floors in buildings significantly influence PED boundaries. Moreover, the type of energy utilized plays a pivotal role in this determination. To meet net-zero carbon targets within PEDs, the deployment of clean energy sources is imperative, making the use of biomass and natural gas appropriate for these areas. Although high-density construction is often perceived as a threat to open spaces, it can yield ecological advantages, such as optimized land, material, and energy utilization. Additionally, it provides socio-cultural benefits, including functional diversity at the ground level and improved urban organization (PED–ID, 2025). Consequently, areas characterized by high building density may be suitable for PED development. The identification of viable locations for energy infrastructure installations presents a considerable challenge, particularly in densely populated urban regions that experience spatial constraints (Derkenbaeva et al., 2021). As a result, population density must be factored into the determination of PED boundaries. Finally, it is crucial to consider social factors, as a higher socio-economic status and level of education among residents will facilitate awareness and adaptation to the PED concept.

3.2.3 Three-Dimensional Data for Mapping PED

The study analyzed solar energy using Ladybug Tools and both solar and wind energy through Autodesk Forma. Direct sun hours were assessed using Ladybug Tools, while solar potential and wind analysis were conducted with Autodesk Forma to evaluate Kadıköy in terms of its solar energy potential and wind energy. The results of these analyses for a designated segment of the study area are presented in Figure 4, Figure 5, and Figure 6.

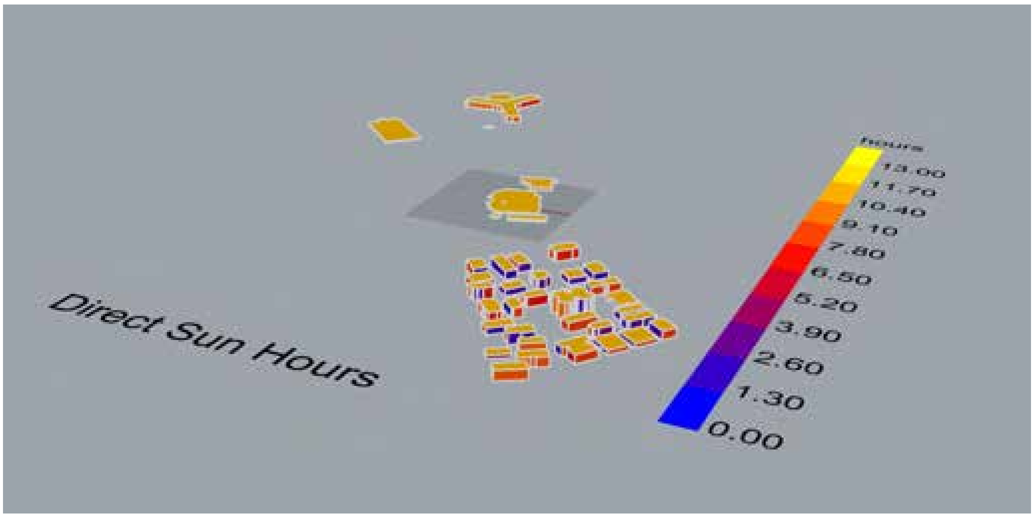


Figure 4. Results of direct sun hours analysis.

The Direct Sun Hours analysis, presented in Figure 4 and utilizing Ladybug Tools, enables a thorough evaluation of the historical sunlight exposure experienced by the roofs and facades of various buildings. In this analysis, the duration of sun exposure for the region depicted in the figure during August was examined. The study revealed that the maximum duration of sun exposure was 13 hours. This analysis is instrumental in identifying the most suitable locations for the installation of solar panels, thereby facilitating the generation of solar energy from renewable sources. Such insights are critical for the development of PEDs and allow for a comprehensive assessment of the solar potential of buildings across different seasons.

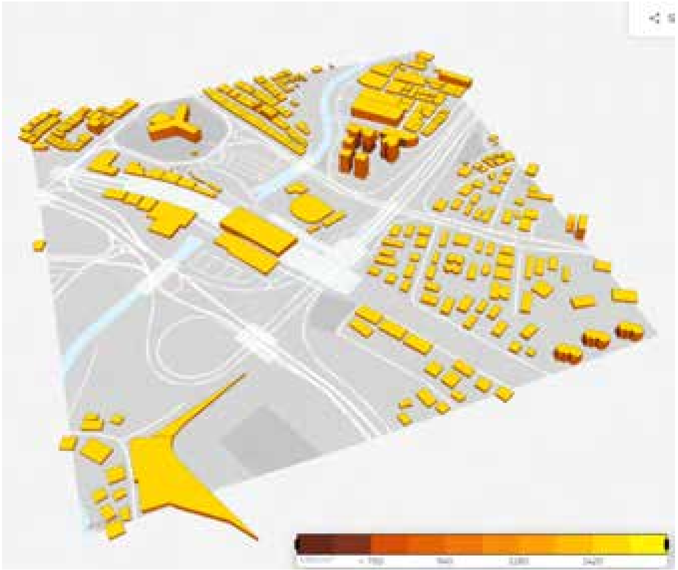


Figure 5. Results of solar potential analysis.

The solar potential analysis carried out utilizing the Autodesk Forma platform, as illustrated in Figure 5, facilitates the assessment of solar potential across various buildings, including their roofs and facades. This comprehensive analysis enables the calculation of the overall solar potential for the region, as shown in the figure. The results indicate that the annual solar energy generation for the area represented in the figure amounts to 221,000,000 kWh, with an average solar energy yield of 1,080 kWh/m².

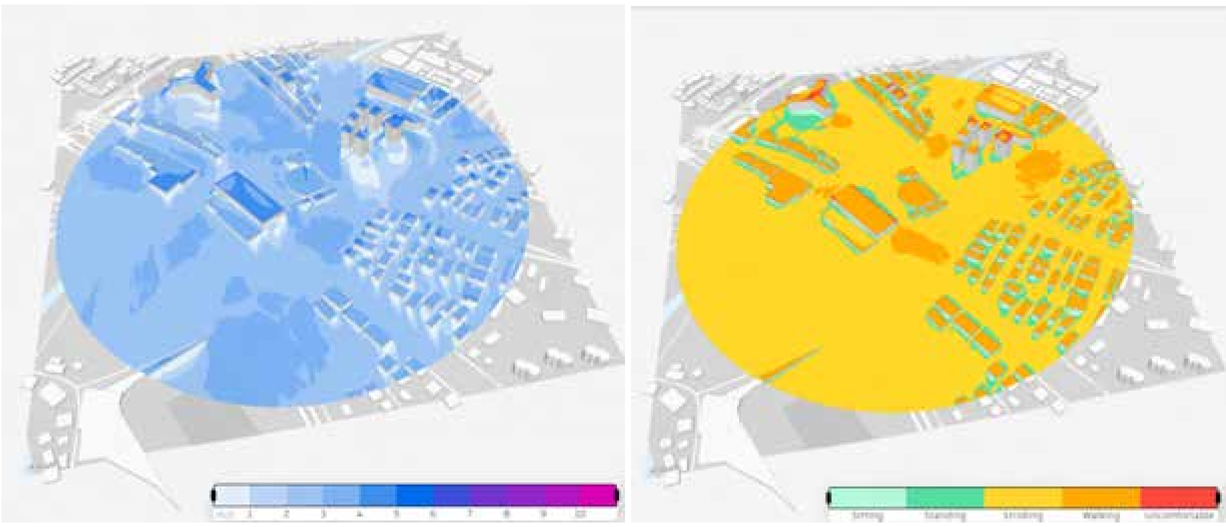


Figure 6. Results of wind analysis.

The wind analysis illustrated in Figure 6 facilitates the examination of how winds originating from various directions affect wind potential and variations in wind speed within the region. Furthermore, this analysis permits an assessment of the wind potential for both buildings and the surrounding terrain. By conducting this evaluation, stakeholders can gain insights into the wind energy potential in urban areas and identify regions with significant capacity for renewable energy production.

3.2.4 Evaluating Results

This study identifies that electricity consumption and GHG emissions are the most critical criteria for assessing suitable areas for the development of PEDs, as determined by the BWM used in MCDM. Regions with low levels of these two criteria are considered more favorable for PED development. However, it is essential to consider additional factors, such as building age, number of floors, type of energy source, building density, population density, socioeconomic status, and education level, which also significantly influence the suitability of development areas.

From an environmental standpoint, regions capable of utilizing clean and renewable energy sources, such as biomass and natural gas, are deemed appropriate for PED development due to their potential for producing clean energy. Furthermore, an analysis of solar and wind energy potential demonstrated that areas with extended sunshine durations and favorable wind patterns are advantageous for renewable energy production.

From a social perspective, the findings indicate that the PED concept can be effectively implemented in regions with high socioeconomic scores and elevated education levels. Residents in these areas typically exhibit greater awareness and sensitivity towards sustainability. Additionally, as education levels rise, individuals' understanding of innovative energy technologies and their ability to adapt to these advancements also improve. This adaptability facilitates the integration of technological infrastructures, such as smart grids, energy monitoring systems, and energy production and sharing applications, all of which are essential for the successful implementation of the PED concept.

Neighborhoods with higher socioeconomic levels often feature more organized and planned urban areas. Consequently, projects developed in collaboration with local governments can be executed more efficiently, leading to increased effectiveness. These characteristics enhance urban resilience and improve adaptive capacity in the face of climate change, contributing to the successful and sustainable implementation of PEDs.

4. Conclusion

In this study, the integration of both 2D and 3D spatial analyses together with a holistic approach to determining the boundaries of PEDs significantly increased the accuracy and applicability of the findings. The use of 2D data was effective in assessing the spatial distribution of PED criteria. Variables such as electricity consumption, GHG emissions, population density, building density, education level, and socio-economic indicators were mapped, and more favorable areas for PEDs were evaluated. Regions characterized by low GHG emissions and energy consumption, in particular, emerged as significant criteria. Additionally, building stock characteristics, such as building age and number of floors, were analyzed in terms of energy efficiency and the integration of renewable energy sources.

The use of 3D data, combined with 3D analyses, facilitated a comprehensive and detailed assessment of solar and wind energy potential. Studies of sunlight duration and annual solar energy production potential conducted using 3D building models allowed the determination of optimum roof and façade surfaces for solar panel installation. These assessments also allowed the assessment of energy potential in various temporal dimensions. Similarly, wind energy potential was analyzed at a micro-scale, taking into account prevailing wind directions. These analyses directly contributed to the shaping of energy production strategies for PEDs by enabling the assessment of local renewable energy resources. By synthesizing both 2D and 3D data, the study presents a comprehensive assessment that addresses horizontal dimensions, such as urban sprawl and density, as well as vertical factors, including sunlight, building height, and wind effects.

To conclude, the findings emphasize the need for a multi-criteria approach to PED planning that transcends energy-centric considerations by integrating social, structural, and environmental dimensions. This comprehensive approach provides a vital foundation for the development of PED models consistent with sustainable urbanism principles.

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