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Leveraging Positive Energy Districts Surplus for the Achievement of the Sustainable Development Goals

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Abstract: This study explores the role of Positive Energy Districts (PEDs) in promoting sustainable urban development. PEDs, defined as urban areas that achieve net-zero energy import and CO_2 emissions while producing a surplus of renewable energy, have gained attention as a promising solution to the challenges of urban sustainability. This research presents a comprehensive methodology for assessing the impact of PEDs on key United Nations' Sustainable Development Goals (SDGs), such as energy accessibility (SDG 7), sustainable cities (SDG 11), and climate action (SDG 13). By examining a case study of a potential PED in Southern Italy, this study demonstrates that PEDs can not only produce sufficient energy to meet their electrical demands, but also support up to 30 low-income households through surplus redistribution, offering an estimated annual economic savings of EUR 1145 per household. Thus, this surplus energy redistribution highlights the practical potential of PEDs to alleviate energy poverty, enhance social equity, and foster community solidarity, thereby extending their impact beyond energy sustainability. Additionally, the correlation between self-consumption and virtual distribution is equal to 0.83, suggesting that PEDs with high self-consumption are also actively involved in virtual distribution, posing the condition for efficient energy use.

Keywords: performance indicators; environmental; economic; social; urban areas; buildings

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1. Introduction

The built environment is energy intensive, using more than the 60% of the energy consumption worldwide [1] and, as cities are hubs of economic activity and population density, they are central to steering the trajectory of sustainable development. In this framework, the energy demands of the built environment in urban areas make cities key players in the transition to more sustainable energy systems. Central to this transformation is the emergence of Positive Energy Districts (PEDs), which represent an example of how urban habitats can evolve to meet the diverse objectives related to environmental sustainability and energy efficiency.

The European Union, recognizing the criticality of this evolution, includes the PEDs through its "Positive Energy Districts for Sustainable Urban Transformation" initiative, nestled within the broader SET-Plan's "Smart Cities and Communities" directive [2]. According to the definition, a Positive Energy District (PED) can be considered as a "district with annual net zero energy import and net zero CO_2 emissions, working towards an annual local surplus production of renewable energy" [3]. The interests in PEDs can be traced back to the European Union's "Clean Energy for All" package, which also brought the formation of energy communities, another example of cooperative urban energy structures [4].

PEDs are characterized by their positive energy surplus [5] and their ability to address environmental, economic, and social sustainability targets [6]. The literature highlights the potential of localized energy production in enhancing district resilience and achieving sustainability goals through collaborative approaches [7]. Incorporating storage systems further reduces grid dependency, enabling community-centric energy-sharing configurations [8]. Key technological and operational features include redistribution within and between districts [9], intelligent building-to-building interactions [10], and energy trading with larger grids [11]. Advanced models have also been developed to assess PED performance. For example, Derkenbaeva et al. employed an agent-based model to evaluate the impact of human-centric behavior on PED pathways, examining energy efficiency and CO_2 emissions reduction [12]. In another study, the integration of agent-based models and fuzzy-logic has been used to evaluate PED contribution toward European sustainability targets for 2020, 2030, and 2050 [13]. Other studies have proposed strategies to improve underperforming buildings [14] and implement energy renovation strategies necessary to achieve the PED status [15].

A consistent amount of literature is debating the constraint of having a net-positive surplus. Gabaldon Moreno et al. introduced a model to measure energy balance within a specific district [16]. They defined the district's perimeter, followed by assessing energy requirements, consumption, and localized generation to assess the final energy balance. The need to have clear and well-defined boundaries also emerge from the surveys and interviews involving engineers, communication experts, and environmental scientists [17]. Apart from retrofitted residential buildings [18], positive balances have been assessed for university campuses [19], non-residential buildings with a bioclimatic design [20], and social housing [21]. The importance of a quantitative energy balance is evident, constituting it as an essential element needed to allow the certification and standardization process [22].

Therefore, as emerging from the cited literature, PEDs are conceived as an urban form able to impact on the environmental, economic, and social dimensions. To this scope, the concept of sustainable PEDs seeks for innovative procedures to balance the pillars of sustainability without having one of the before-mentioned dimensions prevailing on the others [23]. Any technological and operational improvement should be measurable and performances should be quantified to allow for cross comparisons [24]. In addition, the challenge, and also the potential, resides in coherently channeling the positive surplus of PEDs in order to contribute to the aforementioned sustainability of urban areas [25]. In this direction, the Sustainable Development Goals (SDGs) Framework comes to the aid. In fact, SDGs may be helpful to define a structured approach useful to strengthen the beneficial impacts of PEDs in terms of urban sustainability.

The United Nations' Sustainable Development Goals (SDGs) outline a comprehensive framework of 17 goals, 169 targets, and 232 indicators within the "2030 Agenda for Sustainable Development" [26–28]. Among these, SDG 7 focuses on affordable, reliable, and sustainable energy, and holds particular relevance to PEDs. Achieving SDG 7 not only advances energy efficiency and accessibility but also positively impacts health, economic development, and community inclusion. The framework's flexibility enables its integration into specific contexts, such as PEDs, which contribute directly to SDG 7 and intersect with other goals, including SDG 11 (sustainable cities and communities) and SDG 13 (climate action). As underscored in [29], in urban areas, PEDs represent a practical pathway to address these interconnected goals by leveraging renewable energy, improving energy efficiency, and fostering collaborative energy-sharing systems. By aligning PED objectives with relevant SDGs, such as energy accessibility and climate action, PEDs can serve as catalysts for urban sustainability and societal progress.

Despite the aforementioned models and implementation strategies, comprehensive guidelines on surplus energy utilization to enhance district energy performance and promote sustainable evolution remain relatively uncharted. The transition towards sustainable urban areas needs a holistic vision that delves deep into the impact that PEDs can have in terms of the achievement of environmental, economic, and social targets envisioned by the SDGs. In this direction, this study aims at directing PEDs planning in alignment with SDGs, especially those that are directly linked to PEDs. In more detail, the objectives of this study are the following:

- To propose a procedure to demonstrate how PEDs can directly contribute to the sustainable development of urban areas and to the achievement of pertaining SDGs;
- To evaluate how the energy surplus originating from the renewable production can be sustainably leveraged to target other SDGs;
- To develop tailored indicators to measure the PED's impact in terms of SDGs achievement.

With respect to the above-listed objectives, this paper aims to develop a procedural framework outlining step by step how PEDs can be planned, implemented, and managed in order to achieve specific SDGs. In this perspective, it is of utmost importance to establish the identification of the sources of energy production, the quantification of the energy flows within the district, and the amount available for additional uses. This quantitative analysis is strategic to leverage surplus energy by assessing environmental, economic, and social impacts. This can be achieved by developing tailored indicators for measuring progress towards SDGs that are relevant for PEDs. These indicators are inspired by the SDGs' indicators and then customized to reflect the specific context of PEDs.

Results from a candidate PED area previously derived in [30] and are discussed here. The proposed modeling procedure and the defined indicators are not country-specific, thus permitting them to easily replicate their quantification for different case studies and allowing for cross-comparison among PEDs of different countries.

The remainder of this paper is structured as follows. The Section 2 introduces a four-step procedure to delve into the evaluation of the energy surplus of PEDs and how to allocate it in a sustainable way. Subsequently, the case study selected for the analysis is presented in Section 3 and, in Section 4, the results of the modelling procedure and the redistribution of energy surplus in the area to achieve specific goals is discussed. Finally, limitations and implications of this study are discussed and the conclusion is drawn.

2. Materials and Methods

The implementation of PEDs in urban areas may be considered as a way to foster the sustainable transition advocated by the United Nations. To assess how effectively the implementation of PEDs contributes to achieving one or more SDGs, and concurrently gauge the impact of the positive surplus generated by the installation of renewable energy-based production systems, this research proposes the iterative procedure reported in Figure 1.

2.1. Step 1: PED Implementation and Positive Surplus Evaluation

The first step of the elaborated approach consists in the PED's definition and positive surplus evaluation. The term "positive" in PEDs emphasizes, indeed, that these districts produce more energy than they consume. Therefore, evaluating the positive surplus involves calculating the net energy output after considering the energy consumption of the district. Although being a simple balance between the energy produced by renewable sources and the energy consumed at the district level, the calculation of the energy surplus at the district level requires a wide set of data, ranging from spatial data (urban scale, geographical boundaries of the districts) to technological data (energy production technology, energy sources—solar, wind, geothermal, etc.—configurations and efficiencies), and including information on the number of buildings, as well as physical and geometrical parameters as the number of floors, height, surface, volume, and available rooftop areas, number of occupants, and eventual energy-trading mechanisms.

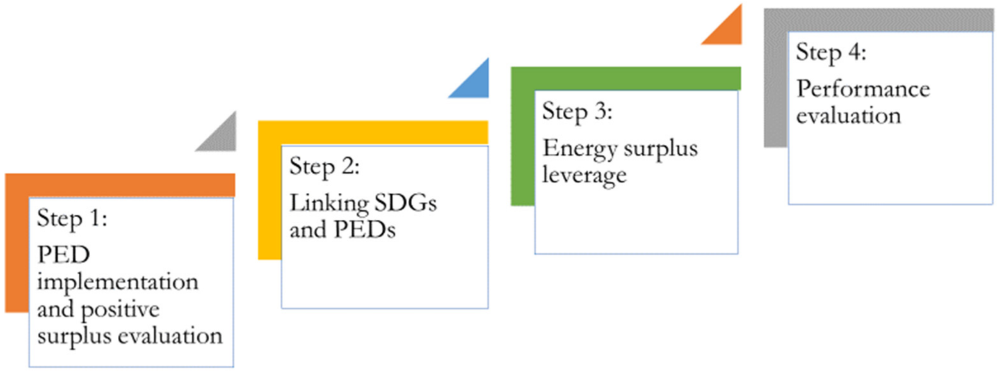

Figure 1. Procedure for performance evaluation of PEDs based on the SDGs.

As said, this surplus is not only a measure of the district's efficiency, but also its potential contribution to the achievement of the SDGs. To perform such an analysis, a tailored modeling approach is needed. By applying the model developed in previous research by the authors [30], the foremost goal of this study is to evaluate how the achieved positive surplus can be converted into a concrete contribution towards the achievement of related SDGs. Each building j within the PED has its own energy demand $E_{dem,j}$ and potentially its own energy production $E_{prod,j}$ from renewable sources. The goal of the model is to optimize the distribution of this energy to achieve the highest level of self-sufficiency, minimizing the reliance on external power grids. To this scope, the objective function can be expressed as

$$\min \sum_{j=1}^{n} E_{g,j} \tag{1}$$

In Equation (1), $E_{g,j}$ is the net imported energy from the grid and n is the total number of buildings in the PED. The model includes the following constraints to ensure that the energy needs of each building are met and that the energy flows are physically feasible. The first constraint refers to the demand and, in particular, the sum of energy produced $E_{prod,j}$ and energy imported from the grid $E_{g,j}$ must be greater or equal to the energy demand for each building:

$$E_{prod,j} + E_{g,j} \geq E_{dem,j}, \forall j \tag{2}$$

In addition, the energy imported from the grid should be non-negative for each building:

$$E_{g,i} \geq 0, \forall j \tag{3}$$

This mathematical formulation permits it to gain awareness on the different energy flows within the PED. In particular, beyond the energy demand and energy production of the area, it is also possible to calculate the amount of energy that is self-consumed from buildings, i.e., in terms of energy that is immediately consumed from renewable production, the energy that is distributed within the district, and the virtual balances within the PED for distribution and with the main grid. Indeed, in this first stage, it is supposed that the PED still maintains its reliance to the grid, to fulfill the demand in case of insufficiency or to serve as a reservoir to account for the mismatch between production and demand. With this specification, the model can be extended not only to PEDs, but also to existing areas in their transition towards the PED paradigm.

2.2. Step 2: Linking SDGs and PEDs

With a clear understanding of the energy flows within the PED, the next step is to establish a connection between the PEDs and the SDGs. This involves mapping how the various components and energy assets of PEDs align with the broader objectives of SDGs. SDG 7, "Ensure access to affordable, reliable, sustainable and modern energy for all", is probably the most relevant goal to be analyzed for the performance evaluation of PEDs. Indeed, the renewable energy aspect of PEDs directly contributes to SDG 7 (affordable clean energy), while the decentralization and community-focused design of PEDs can be linked to SDG 11 (sustainable cities and communities). These connections are immediate, due to the intrinsic essence of PEDs. However, PEDs also contribute to SDG 12 (responsible consumption and production) and to SDG 13 (climate action). Table 1 reports the list of SDGs, targets, and chosen indicators.

Table 1. Some examples of PED-related SDGs.

SDG	Target	Indicator	SDG	Target	Indicator
SDG 7	7.1	7.1.1	SDG 11	11.1	11.1.1
		7.1.2		11.2	11.2.1
	7.2	7.2.1		11.3	11.3.1
	7.3	7.3.1		11.6	11.6.2
	7.b	7.b.1		11.a	11.a.1
SDG 12	12.7	12.7.1	SDG 13	13.2	13.2.2
	12.a	12.a.1			

Among the different targets and indicators of SDG 7, the most representative ones chosen in this study are the following:

Target 7.1: "*By 2030, ensure universal access to affordable, reliable, and modern energy services*". This target is measured by two indicators, 7.1.1 and 7.1.2, referring to the access to electricity and primary reliance on clean technologies, respectively. The indicator 7.1.1 is expressed as a percentage by the UN and, usually, data mostly cover the developing countries [31]. The indicator 7.1.2 refers to "clean" technologies, i.e., related to the emission rate targets against fossil fuels [32].

Target 7.2: "*By 2030, increase substantially the share of renewable energy in the global energy mix*", here measured by the indicator 7.2.1 expressed as the percentage of final consumption of energy deriving from renewable sources [33]. More particularly, this indicator considers the amount of renewable energy effectively consumed and not the installed renewable capacity. According to this formulation, it is possible to exclude bias and distortions deriving from intermittency of renewable sources (difficult to take into consideration) and energy losses along the entire energy production and distribution chain [33].

Target 7.3: "*By 2030, double the global rate of improvement in energy efficiency*", for which the indicator 7.3.1 on the dependence of the energy intensity with economic outputs has been formulated. The UN defines the energy intensity as the amount of energy used to produce one unit of economic output and expressed in terms of GDP [34].

Target 7.b: "*By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States and landlocked developing countries, in accordance with their respective programmes of support*", measured by indicator 7.b.1 on the installed renewable energy per capita. This indicator refers to developing countries, and has significant impacts in the environmental, economic, and social dimensions [35]. Tracking progress for this indicator will also result in the enhancement of Target 7.1 indicators.

The diffusion of PEDs can also realize the SDG 11: "Make cities and human settlements inclusive, safe, resilient and sustainable". The targets and indicators here included are the following:

Target 11.1: "*By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums*", measured by indicator 11.1.1 on the proportion of population living in inadequate housing, as, for example, in case of overcrowding, poor structural quality, or durability of dwellings [36].

Target 11.2: "*By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons*". Here, the indicator 11.2.1 measures the proportion of population with convenient access to the public transport sector. The access is considered "convenient" if the distance from a reference point to the station is achievable with a 500 m walk (in case of buses) or 1 km (in case of trains, metro), as defined by the UN guidelines [37].

Target 11.3: "*By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries*". The indicator 11.3.1 could be helpful to highlight the impact of PEDs on land use.

Target 11.6: "*By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management*". Among the different indicators that underlie the achievement of this target, here the 11.6.2 has been selected as particularly relevant for PEDs' performance evaluation, which refers to the annual levels of particulate matter in urban settlements and, therefore, directly correlates to air pollution [38].

Target 11.a: "*Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning*". The indicator 11.a.1 counts the number of countries with dedicated development plans at both the regional and territorial level. Any progress achieved in this direction emphasizes a global progress in terms of sustainable transition in urban settlements [39]. Therefore, national policies focusing on PED implementation may be recognized as a significant step towards more sustainable urban areas.

PEDs represent an innovative urban form producing more energy than they consume, therefore also aligning with SDG 12: "Ensure sustainable consumption and production patterns". For this goal, the following targets can be considered as crucial for PED-related contexts:

Target 12.7: "*Promote public procurement practices that are sustainable, in accordance with national policies and priorities*" fits for the sustainable performance evaluation of PEDs, in particular, by calculating the indicator 12.7.1 referring to the number of countries implementing sustainable action plans in public organizations.

Target 12.a: "*Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production*". The indicator

12.a.1 is also used as 7.b.1 [40], therefore, although listed among the relevant targets and indicators, will not be included in the analysis due to overlapping issues.

In the context of urgent climate action demanded by SDG 13, "Take urgent action to combat climate change and its impacts", PEDs actively contribute to mitigating GHGs, also considering that they encapsulate this feature in their definition. For this goal, target 13.2, "*Integrate climate change measures into national policies, strategies and planning*", is highly relevant in the case of PED evaluation and can be measured by indicator 13.2.2, accounting for the total greenhouse gas emissions per year and calculated using the Global Warming Potentials as the common weighting factor [32]. This indicator is based on national inventory reports; a complete repository and time series are available from the United Nations Framework Convention on Climate Change (UNFCCC) website [33].

To facilitate the implementation of the SDGs' framework, the Inter-Agency and Expert-Group on SDGs IAEG-SDGs introduced three tiers to group the indicators on grounds of the data availability and methodological advancement [34]. The classification criteria are defined as Tier I (clear definition of the indicator and relevant data availability at the national level), Tier II (clear definition of the indicator and data availability not regular at the national level), and Tier III (unclear definition of the indicator). In this study, all indicators belong to Tier I, except for 11.2.1 and 12.7.1, classified as Tier II. For these last two indicators, it is convenient to refer to case-specific data for PEDs to facilitate calculation or evaluation.

As mentioned, the indicators should be tailored to capture the essential aspects of PEDs, i.e., measuring the amount of renewable energy produced by a PED in a year or the reduction in greenhouse gas emissions due to PED implementation. The indicator 7.1.1 can be calculated as the proportion of population with access to electricity PP_{EA} and indicator 7.1.2 as the proportion of population with primary reliance on renewable-based production technologies PP_{REN}, as reported below:

SDG 7 $$PP_{EA} = \frac{\text{PED occupants with access to electrical services}}{\text{Total PED occupantsoccupants}} \quad (4)$$

SDG 7 $$PP_{REN} = \frac{\text{PED occupants with primary reliance on renewables}}{\text{Total PED occupants}} \quad (5)$$

The indicator PP_{EA} could be considered as immediately satisfied, being the access to electricity granted for occupants of PEDs. To provide a useful analysis, especially for developed countries, this indicator can be referred to as the district before its identification as a PED or to similar districts not yet defined as PEDs. This, however, may not apply to slums or poor areas. The indicator PP_{REN} is evaluated here considering the proportion of population with installed renewable technologies on or in proximity to their houses. To calculate this indicator, it has to be distinguished between the proportion of population living in buildings or houses in which renewable production technologies have been effectively installed and the population belonging to the PED but not actively contributing to the renewable production, such as those occupants that do not have PV installed on their rooftops.

The indicator 7.2.1 refers to the percentage of renewable energy in the total final energy consumption of the PED. Therefore, it can be calculated by considering the total renewable production from installed technologies in each building j and the energy demand of each building j of the district, as reported in Equation (4):

SDG 7 $$REN_{share} = \frac{\sum_{j=1}^{N} E_{prod}}{\sum_{j=1}^{N} E_{dem}} \cdot 100 \quad (6)$$

Referring to indicator 7.3.1, it can be useful to correlate the energy production with the economic sphere in terms of GDP:

$$\text{SDG 7} \qquad \text{EnEc} = \frac{\sum_{j=1}^{N} E_{prod}}{\text{Total GDP}} \tag{7}$$

The indicators for SDG 11 are translated into the PED concept as follows. The indicator 11.1.1 refers to the population living in inadequate housing. Again, PEDs ensure adequate, safe, and energy-efficient buildings. Therefore, the analysis of this indicator may help in comparing PEDs to the regional or national reference values or to similar districts not yet recognized as PEDs. It can be expressed as

$$\text{SDG 11} \qquad \text{PP}_{\text{housing}} = \frac{\text{Occupants with inadequate housing}}{\text{Total occupants}} \tag{8}$$

This indicator may be useful for urban planners and developers as it helps to identify areas where housing conditions are below acceptable standards, thus allowing for targeted interventions and, consequently, resource allocation. In addition, from the social viewpoint, it can also highlight disparities in housing quality and being a starting point for tailored policies focusing on social inclusiveness. The indicator 11.2.1 measures the access to public transport services, here specified as $\text{PP}_{\text{transport}}$ for the case of PEDs:

$$\text{SDG 11} \qquad \text{PP}_{\text{transport}} = \frac{\text{PED occupants with access to public transport services}}{\text{Total PED occupants}} \tag{9}$$

The indicator 11.3.1 measures the impact on land use, here calculated as a measure of urban footprint and related to the metropolitan areas for which indicators are derived:

$$\text{SDG 11} \qquad \text{PL}_{\text{use}} = \frac{\text{urban area covered by PEDs}}{\text{Total urban area of the municipality}} \tag{10}$$

This indicator can be used with a comparative function across municipalities, i.e., to assess the recorded progress in expanding PEDs and replicate the experience in other areas. The environmental dimension for SDG 11 is calculated from the indicator 11.6.2, expressed as the concentration of particulate matter per capita, and here formulated as in PM_{urban} in Equation (9):

$$\text{SDG 11} \qquad \text{PM}_{\text{urban}} = \frac{\text{Air quality (PM 2.5 concentration)}}{\text{Total PED occupants}} \tag{11}$$

The indicator 11.a.1 refers to the development and implementation of action plans and the PED implementation can be considered as progress for the achievement of the goal.

Finally, the indicator 13.2.2 accounts for the percentage of avoided total greenhouse gas emissions per year compared with a traditional supply from centralized fossil sources GHG_{trad}:

$$\text{SDG 13} \qquad \text{GHG}_{\text{y}} = \text{Tons of greenhouse gases per occupants} \tag{12}$$

The calculation of the aforementioned indicators allows us to evaluate the role of PEDs in achieving SDGs closely linked to sustainable urban transition. Yet, solely relying on these indicators might not provide a comprehensive assessment of the potential impact of PEDs on urban regions and their alignment with sustainability goals. It is crucial to also understand how the positive energy surplus might be applied in this context.

2.3. Step 3: Energy Surplus Leverage

Having established the link between PEDs and those SDGs to which they directly contribute, the next step is to develop specific indicators that measure the impact of PEDs' surplus to other relevant SDGs. Indeed, assessing indirect connections or, generally, achievement of specific goals due to the impact that the surplus energy or the net-zero balance may have on the territory, is pivotal. Establishing these links provides a comprehensive framework for understanding how PEDs can drive sustainable development on a global scale. These correlations as well as the indicator formulation and description are presented in Table 2.

Table 2. Second-stage indicators for energy surplus allocation.

SDGs Impacts	Indicator Formulation	Description	Correlations	
SDG 1 SDG 10	$\frac{H_{aff,energy}}{H_{region}}$	Number of households in underserved areas or in energy poverty conditions gaining access to affordable energy through PEDs	SDG 7 SDG 11	(13)
SDG 1 SDG 10	$\frac{EC_{trad} - EC_{PED}}{EC_{trad}}$	Economic savings for marginalized groups due to PED savings and sustainable redistribution in the area	SDG 7 SDG 11	(14)
SDG 12	$\frac{\sum_{j=1}^{N} E_{cons,j}}{\sum_{j=1}^{N} E_{prod,j}}$	Energy consumption efficiency due to PEDs	SDG 7 SDG 11 SDG 13	(15)

Indicator (13) measures the number of households in underserved areas or in energy poverty conditions that gain access to affordable energy through PEDs. This indicator is primarily linked to SDG 7 and SDG 11, as it relates to energy access and urban sustainability. Equation (14) presents an indicator that calculates the economic savings within PEDs. It reflects the difference between energy costs of the supply from centralized power grids, EC_{trad}, and those within PEDs, EC_{PED}, showing the economic benefit to marginalized communities. Like the previous indicators, this also correlates with SDG 7 and SDG 11, highlighting the financial benefits of sustainable energy practices within PEDs for low-income families. Finally, the indicator in Equation (15) represents the energy consumption efficiency within PEDs. It is calculated by dividing the total energy consumed, E_{cons}, by the total energy produced, E_{prod}, across all users within the PED. This indicator is related to SDG 7, SDG 11, and SDG 13, as it touches on energy efficiency, urban sustainability, and climate impact through efficient energy use.

In addition to the abovementioned metrics, the indicator 12.7.1 may become relevant for PEDs' impact assessment in the case of active enrollment in the district of public organizations or public administrations, such as municipalities [41]. In the case of public procurement inside the PED, it can be considered achieved.

2.4. Step 4: Performance Evaluation

The final step involves using the developed indicators to evaluate the performance of PEDs in real-life contexts. This step encompasses several activities, including collecting data, detailed analyses, and drawing conclusions about the effectiveness of PEDs in achieving the SDGs. Performance evaluation not only provides insights into the current state of PEDs' contribution to SDGs but also offers guidance for future improvements and diffusion. To properly evaluate the impact of the positive surplus of PEDs, annual national or regional values may serve as the baseline.

In addition, it is also important to define if the values of energy produced, self-consumed, and distributed within the PED are correlated and to what extent. To pursue this analysis, the Pearson correlation coefficient formula can be used. By employing this calculation, it is possible to quantitatively evaluate the degree of association between these variables. Therefore, this analysis is useful to evaluate the operational synergies within PEDs but also provides valuable information that can guide strategic decisions aimed at optimizing energy distribution and consumption patterns within these districts.

These indicators are independent to allow the consideration of specific challenges and opportunities within PEDs. Using independent indicators is important as it enhances transparency in the evaluation process, making it easier to justify any decisions. They also permit to identify areas for improvement and support any informed decision-making process aiming to lead to more efficient and sustainable urban energy solutions. Lastly, the independence of the indicators ensures that the evaluation framework is both scalable and adaptable to PEDs of varying sizes and in different urban contexts, such allowing for replication.

3. Case Study

A specific district in Catania, Southern Italy, falling under climate zone B, consists of two dozen buildings. Primarily designed for residential purposes, these buildings are illustrated in Figure 2. The district supports a population of approximately 407 residents and is a workplace for 45 individuals. The chosen area is not yet a PED, but may be considered as a viable candidate, with it working to the constitution of a renewable energy community, according to the normative, technological, and operational constraints of the European Directive 2018/2001 [35] and the Italian transposition, Law 199/2022 [36]. A detailed explanation of the case study can be found in [30]. In detail, the area consists of twenty buildings, predominantly used for residential purposes. Most of these residential buildings are similar in terms of area, with living spaces being around 250 m^2. These are typically buildings with three floors. A couple of houses are smaller, with one being under

100 m^2 and another around 130 m^2, with inhabitants from three to nine people. The area also comprises two larger residential buildings, each with a total floor area of approximately 480 m^2 and 64 inhabitants in each. On the commercial front, there are three buildings: one at around 143 m^2 and the other two spanning over 640 m^2.

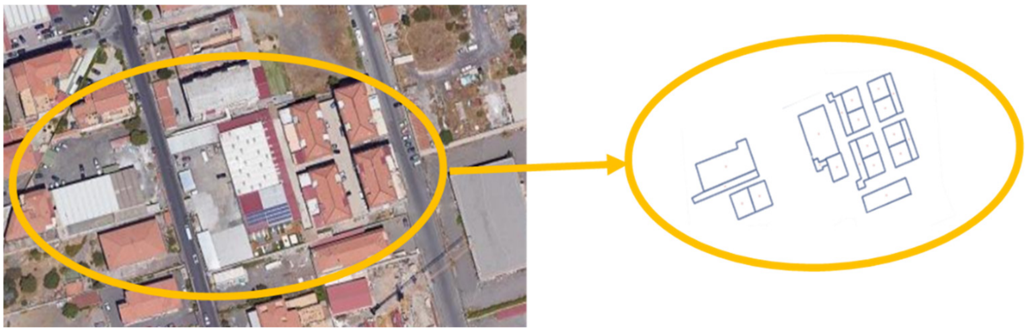

Figure 2. Case study area.

Energy-related data were sourced from property owners and commercial establishments that are part of the district. Aggregate electrical consumption data were provided, necessitating estimated breakdowns for each structure. The electrical demand was inferred by combining this data with insights from a prior survey of a similar district. This led to an annual electrical demand estimation for the district at approximately 374.89 MWh$_{el}$. Photovoltaic (PV) electrical output was determined using the area's global irradiance and a 65% conversion factor for net electricity generation, as proposed by Huld [37]. Monthly direct normal irradiation values were sourced from the Global Solar Atlas [38]. PV panel setups are included in the study accounting for technical limitations, rooftop space, maintenance and cabling areas, roof type, tilt, and potential shading. The model simulates the ideal electrical balance for varying geographical boundaries to understand the inter-building electricity flow dynamics under the PED concept.

4. Results and Discussion

The optimized results for the candidate PED are detailed and discussed herein. Electrical demand, production, and self-consumption from PV, as well as exceeding electricity, for each building is plotted in Figure 3. Indeed, buildings contribute to the SDGs' achievement either through self-consumption, providing excess energy, or participating in virtual distribution. Self-consumption indicates the energy used directly from production, contributing to SDG7 and SDG 11; the exceeding production reflects surplus energy that could be stored or shared, supporting SDG 7 and, potentially, SDG 11 and SDG 13, by proper allocation. Virtual distribution shows the energy distributed within the PED, again contributing to SDG 7 and SDG 11.

Electrical output from the panels differs due to the aforementioned constraints. As can be observed, for 10 buildings out of 20, PV output predominantly meets the electrical demands. Some buildings, such as 18, 19, and 20, possess expansive PV installation space, resulting in PV production exceeding 50 MWh/y in some instances. Other buildings produce electricity that exceeds their consumption, making it available for contributing to the net-positive balance of the area.

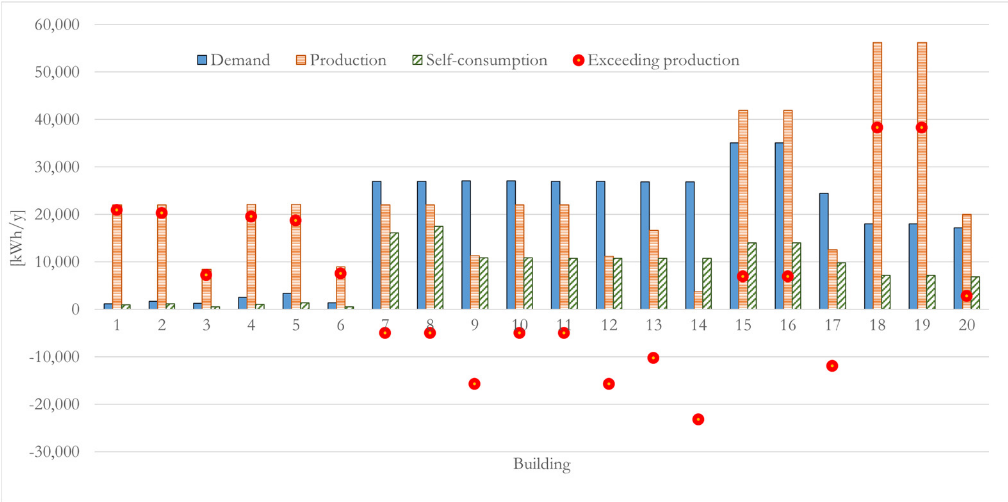

Figure 3. Electrical balances in the PED.

As emerging from Figure 3, a substantial electricity amount is exported to the grid, representing the portion of exceeding production. This surplus electricity offers multiple options for the PED: it can be stored in batteries to counteract the inherent intermittency of renewable sources like solar, promote electric mobility, or be redirected to assist underserved and low-income households, in line with the United Nations' Agenda 2030 and Sustainable Development Goals recommendations.

Before deepening how the exceeding electrical surplus can be allocated, the PED capabilities in terms of achievement of the SDGs indicated in Table 1 should be evaluated. To this scope, the indicators from Equations (4)–(12) have been calculated, taking into consideration baseline values.

The first target of SDG 7 can be measured by two indicators, 7.1.1 and 7.1.2, indicating the proportion of population with access to electricity and with primary reliance on renewables, respectively; in the context of PEDs, they can be calculated as in Equations (4) and (5). Regarding the first indicator, PP_{EA}, it is the proportion of PED occupants with access to electrical services with respect to the total number of PED occupants. In this case, given that access to electricity is granted for occupants of PEDs (especially for developed countries), this indicator can be considered as immediately satisfied, with values at 1 or 100%. The indicator PP_{REN} is the proportion of PED occupants with primary reliance on renewables. At rigor, PEDs are urban forms in which energy should be produced by renewable sources; still, this aspect is not explicit in the actual available definition, and, therefore, it is common to refer to a net-zero balance. To calculate this index, the number of PED occupants with installed renewables technologies (as in this case, PVs) with respect to the total number of occupants should be calculated. In this study, given the heterogeneity of the PED's population, both occupants and workers are included in the analysis. Target 7.2 refers to the percentage of final consumption of energy deriving from renewable sources. The indicator refers to the renewable energy produced and used for self-consumption or distribution within the PED, and is not indicated in terms of installed power size: in the case of PED implementation, it is described by the indicator REN_{share}, particularized from the UN indications. Having a value higher than the unity indicates a positive surplus from the balance of demand and production. Target 7.3 correlates the dependence of the energy intensity with the economic sphere, here with the declination in GDP. For the context of a PED, calculating the GDP would be unconventional since GDP is typically associated with countries or larger economic regions, not specific districts. However, for this study, it can be assumed as the mean Sicilian value, which was around EUR 87 billion for 2022 [40].

For the realization of SDG 11, four indicators are calculated as reported in Table 3. It has been chosen to report the national values. It is worth noting that these data may be easily reproduced for any country from the consultation of national statistics and reports or from the UN website [26]. For the general indicator 11.1.1 on the proportion of population living in inadequate housing, here specified for PED occupants, $PP_{housing}$, the value is again approximated to 1, from the definition of PED itself. In this sense, it can be immediately stated that the diffusion of PEDs in urban areas contributes to the achievement of target 1.1. of SDG 11. Regarding indicator $PP_{transport}$, representative of the target 11.2, data of the simulated scenarios do not permit to infer appropriate conclusions and is, therefore, not possible to calculate in this study. Still, it is maintained in the proposed evaluation procedure to account for general applications. The indicator PL_{use}, useful to refer to the target 11.3 on sustainable urbanization, can be considered as a measure of the urban footprint, i.e., the impact on land use. It can be calculated, as per Equation (8), that is considering the urban area covered by PEDs and compared with the area of the municipality in which the PED is going to be implemented. The simulated area is part of a small municipality in Catania; therefore, the value of the covered territory from PED is significantly high. Target 11.6 refers to the annual particulate matter per capita. In this case, the reference value is calculated by making the hypothesis for which the average levels of the PM concentration remain comparable to the case with and without PED. Finally, in the context of SDG 13, even in this case it can be supposed that the average percentage of avoided GHG emissions is equal to 100%, given that PEDs are urban areas with a net-zero emissions balance.

Table 3. Comparison of the baseline values for the selected SDG indicators in Italy [39] with the simulated outputs for the examined case study area.

SDG	Target	Indicator	Baseline Value (Italy)	Simulated Value
SDG 7	7.1	PP_{EA}	0.92	1
		PP_{REN}	0.88	0.67
	7.2	REN_{share}	0.351	1.62
	7.3	EnEc	0.93	N.A.
SDG 11	11.1	$PP_{housing}$	0.834	1
	11.2	$PP_{transport}$	0.693	N.A.
	11.3	PL_{use}	-	0.57
	11.6	PM_{urban}	0.717	0.717
SDG 13	13.2	GHG_y	7 ton/inhab	Net-zero

At this point, it is of crucial importance to define the impact of PED surplus on the other identified SDGs, as reported in Table 2. The exceeding electricity, indeed, could be used to contribute to SDG 1 on energy poverty, SDG 10 about the need of reducing inequalities, and SDG 12 focusing on responsible production and consumption. SDG 1 and SDG 10 are influenced by SDG 7 and SDG 11 and their achievement can be measured by the indicators in Equations (13) and (14), referring to the number of households in underserved areas or in energy poverty conditions gaining access to affordable energy produced within the PED and to the economic savings for marginalized groups arising from the energetic supply from PED, respectively. Basically, the two indicators give insights into how families in energy poverty conditions can be supported from the PED production, both energetically and economically. These calculations can be pursued by considering the average energy consumption of a family in Italy of around 2300–3200 kWh/year [41]. In this case, from the obtained electrical balance of the PED, around 28–30 families can be supported, with a net economic savings of 1145 EUR/y per family, related to the specific cost of energy [41]. Thus, as has emerged from these initial results, PEDs not only bring benefits in terms of energy efficiency and emission reduction, but also have a significant impact on social dynamics and long-term urban development. The redistribution of the energy surplus to households in energy poverty conditions, as calculated here, improves living conditions, fosters the communitarian sense of solidarity and, therefore, yields a greater social cohesion within the PED. And, not to be considered as a separate topic from energy efficiency, energy production, and energy distribution, responsible energy consumption models can also bring long-term benefits, such as collaboration among citizens, attraction for local businesses, and close activity with municipal institutions. Having this new way of conceiving the district, and also the city, brings a new way of thinking for urban spaces, promoting investments in sustainable mobility, secure infrastructure, and greener areas.

Beyond renewable production, another important feature of PEDs is energy efficiency and its relationship with the values of self-sufficiency. Energy efficiency can be defined as the ratio of self-consumption and demand, as in Equation (15). From the optimized energy flows and the graph of Figure 3, it can be observed that buildings with higher energy efficiency tend to have higher energy self-sufficiency, indicating a positive relationship between efficient use of energy and the ability to meet demand with production. In this sense, they contribute to the achievement of SDG 7, SDG 11, and SDG 13. Some buildings stand out with particularly high self-sufficiency, suggesting that they produce significantly more energy than they consume. Conversely, buildings with lower efficiency and self-sufficiency indicate potential areas for improvement. In terms of energy performance evaluation, a correlation analysis between the different energy flows (such as energy production, self-consumption, etc.) and their impact on SDGs is pursued. This helps in identifying which factors are the most strongly associated with achieving specific goals.

The heat map of Figure 4 is a matrix that showcases the correlation coefficients between the different energy flows calculated as output from the optimization, i.e., the self-consumption, exceeding production and virtual distribution, along with the aggregated values of the demand and production. The colors typically represent the strength and direction of the correlation. A color gradient from green (positive correlation) to red (negative correlation) is used. The numbers within the cells represent the correlation coefficients between each pair of variables (indicated in the corresponding row and column). A value of 1 indicates a perfect positive correlation, meaning that as one variable increases, the other also increases. A value of -1 indicates a perfect negative correlation, meaning that as one variable increases, the other decreases. A value of 0 suggests no correlation between the variables. It directly emerges from the explanation that the diagonal shows perfect correlations, i.e., with values of 1, as it represents the relationship of each variable with itself. Correlation matrices are symmetric across the diagonal, meaning that the correlation between any variables A and B is the same as the correlation between variable B and variable A. These indications are important since they can provide insights into how different aspects of energy usage and distribution are related to each other and can help in understanding the dynamics within PEDs. The sparkline graphs on the right of Figure 4 present this dataset in a compact and simple way and helps in identifying the highest and lowest values in the data series of the correlations.

	Demand	Production	Self-consumption	Exceeding production	Virtual distribution
Demand	**1.00**	**0.19**	**0.94**	**-0.54**	**0.97**
Production	**0.19**	**1.00**	**0.15**	**0.72**	**0.20**
Self-consumption	**0.94**	**0.15**	**1.00**	**-0.53**	**0.83**
Exceeding production	**-0.54**	**0.72**	**-0.53**	**1.00**	**-0.51**
Virtual distribution	**0.97**	**0.20**	**0.83**	**-0.51**	**1.00**

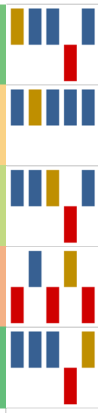

Figure 4. Heat map of electrical flows in the PED and sparkline graph.

In more detail, demand and production share a value of 0.19, indicating a weak positive correlation between energy demand and production. It suggests that an increase in energy demand within the PED does not strongly correlate with an increase in energy production. This implies that energy production capacity is likely not dynamically adjusted based on demand within the PED, possibly due to the nature of renewable energy sources such as solar and wind, which have fixed production profiles that do not respond immediately to changes in consumption patterns. There is a strong positive correlation between demand and self-consumption, at 0.94, therefore implying that as the energy demand in buildings increases, their self-consumption of energy also significantly increases. This indicates that buildings with higher energy demand are effectively utilizing the energy they produce on site, optimizing their internal consumption and reducing the need for external energy supply. The demand and exceeding production show a moderate negative correlation, with a value of—0.54, suggesting that buildings with higher energy demands are less likely to produce excess energy. This could be explained by the fact that energy-intensive buildings may consume almost all of the energy they generate, leaving little or no surplus for storage or redistribution. Demand and virtual distribution have a strong positive correlation (0.97), revealing that buildings with higher energy demands are significantly involved in the virtual distribution network within the PED. This high correlation suggests that energy-sharing mechanisms are effectively utilized in the district, as buildings with greater demand play a major role in both receiving and distributing energy, thereby enhancing grid stability within the PED.

Production and self-consumption have a weak positive correlation of 0.15. This suggests that an increase in energy production is only slightly associated with an increase in self-consumption. This could imply that buildings with higher production capacity may not always use their energy but might be channeling it into the PED's shared network. A moderate positive correlation of 0.72 can be observed between production and exceeding production. This suggests that these buildings have sufficient production capacity to meet their own needs and still produce surplus energy, which can be shared, stored, or exported. This surplus could be utilized for energy storage, shared within the PED, or exported to the grid. The weak positive correlation of 0.2 between production and virtual distribution suggests that increased energy production in buildings has a slight relationship with their involvement in virtual distribution. Other factors such as the energy demand profiles or local energy policies might be influencing the actual distribution decisions. While buildings with higher production are part of the network, their contribution or receipt of energy is not strongly determined by their production capacity.

Self-consumption exhibits a moderate negative correlation of—0.53 with the exceeding production, indicating that buildings with higher self-consumption tend not to have much excess energy. This implies that when buildings are efficiently using the energy they produce, there is limited surplus left for sharing or storage, highlighting a potential conflict between maximizing self-use and generating excess for the community network. The correlation between self-consumption and virtual distribution is 0.83. This strong positive correlation suggests that buildings with higher self-consumption are also actively involved in virtual distribution. This could indicate a balance between efficient self-use and participation in the energy-sharing network.

Finally, the moderate negative correlation between exceeding production and virtual distribution, i.e., −0.51, suggests that buildings with more excess production are less involved in virtual distribution, potentially due to a lack of local energy demand at that moment. This could indicate that buildings having surplus energy might be exporting it to the grid, rather than engaging in the PED's internal energy distribution. This observation can lead towards optimizing energy distribution systems within the PEDs, thus achieving a more efficient local distribution of energy surplus and reducing the need for external energy export.

While the correlations observed in this study refer to the dynamics of energy production, consumption, and distribution, it is also crucial to consider the potential for direct or indirect rebound effects, i.e., when energy savings lead to higher energy demand or where cost savings are spent on goods and services that also require energy. For PEDs, the direct rebound effect might occur when buildings increase their energy use after receiving a benefit in terms of energy surplus or energy bill reduction. This behavior could partly offset the environmental and economic benefits initially achieved through energy savings, ultimately reducing the anticipated positive impact of PEDs on energy consumption and emissions. For the indirect rebound effect, significant considerations can refer to socio-economic aspects, with energy savings potentially increasing new investments in goods or services with a high energy footprint, again diminishing the net environmental benefits of PEDs. To mitigate these effects, it is important to have a prior planning of PED implementation, with strategies including behavioral changes, energy storages, or demand-side systems that can ensure that surplus energy is used efficiently.

5. Policy Implications and Applicability

The PED model presented in this study highlights its potential to drive sustainable urban development and contribute significantly to various SDGs. The findings point to the importance of optimizing energy production and consumption and of dealing with surplus energy allocation to address energy poverty and reduce inequalities. However, the path from theory to practice needs dedicated resources and recommendations. As a first and very important aspect to be considered, there is a clear call for action to develop standardized policy frameworks. The importance of having policy indications lies not only in the need of having clear guidance and regulatory support for urban and energy planners, but also in incentives and financial support that can help the development of PEDs, especially for the case of existing neighborhoods. As an example, subsidies or tax incentives can be devoted to urban projects that meet PED criteria and ensure a sustainable redistribution of the energy surplus among the underserved population to contrast energy poverty. At the same time, the policies should adopt a multi-stakeholder approach, favoring collaboration among local governments, energy providers, building owners, architects and engineers, and urban planners.

At the same time, to properly streamline the process for energy sharing and trading, national governments should also provide regulatory reforms permitting an effective operation of PEDs.

Beyond the regulatory support and proactive policy actions, public engagement and education remain important aspects to be considered when planning any PED development. As a matter of fact, PEDs are made by people, who should be aware of the impact of their choices and of how they contribute to the energy saving and social impact.

Regarding the applicability and broader geographical extension, while this research focuses on a single district in Southern Italy, the methods and findings presented are designed to be adaptable and applicable to a diverse urban context, with the premise of having national available data. The same consideration applies to the model, as it refers to renewable production estimation and surplus distribution, concepts that can be tailored to different geographic, climatic, and socio-economic conditions.

6. Conclusions

The PED model delineated through this research not only showcases the feasibility of energy self-sufficient urban districts but also acts as a beacon for sustainable urban development. By intricately weaving the threads of renewable energy production, energy efficiency, and community engagement, PEDs stand as exemplars for cities of the future. Buildings that produce more energy than they consume could not only serve their own needs but also support their surrounding infrastructures and communities. Moreover, the surplus energy from PEDs, as suggested by the results of this study, holds the potential to tackle energy poverty and reduce inequalities, and promote responsible consumption and production. Among all aspects, energy poverty remains a pressing issue, even in developed nations. By redirecting the surplus energy from PEDs, underserved communities and households can gain access to affordable and sustainable energy. This not only aligns with SDG 1, which targets poverty alleviation, but also resonates with SDG 10, in which the objective is to reduce inequalities. The provision of surplus energy from PEDs to energy-poor households can significantly improve their living conditions, providing them with not only lighting and heating but also the opportunity for social and economic upliftment. Furthermore, the economic savings generated from the PED's surplus energy can empower marginalized groups by reducing their utility expenses. This can lead to improved educational outcomes, better health conditions, and enhanced opportunities for economic development, thereby also contributing to other SDGs, beyond the achievement of SDG 1 and SDG 10. However, it is also essential to consider the rebound effect, where savings on energy expenses could lead to increased energy consumption. The actualization of beneficial outcomes grounds on the capacity to effectively channel the economic savings into areas that are capable of yielding positive social and environmental impacts.

The PED concept emerges as a pivotal paradigm in the transition towards sustainable urbanization. The case study of the district in Southern Italy highlights how the implementation of PEDs can substantially contribute to the achievement of various SDGs, notably SDG 7, 11, and 13. Practically, optimizing energy production and consumption within the framework of a PED not only enhances energy efficiency and reduces the reliance on external power grids but also promotes urban resilience and the quality of life for residents. Theoretically, PEDs reinforce the notion that the integration of renewable technologies and sustainable practices at the district level can lead to positive transformations in terms of energy accessibility, inequality reduction, and climate change mitigation. The model proposed in the present study offers a replicable methodology for assessing the impact of PEDs on SDGs, paving the way for future research and applications in diverse urban contexts. PEDs inherently encourage responsible production and consumption, in line with

SDG 12. The surplus energy is redirected to serve the greater community good. The notion of self-sufficiency within PEDs, where buildings produce more energy than they consume, demonstrates that urban areas can be not just consumers of resources, but also producers, contributing to a sustainable urban ecosystem. Furthermore, the relationship between energy efficiency and self-sufficiency within PEDs confirms the potential of integrated urban energy systems; buildings with higher energy efficiency tend to have higher self-sufficiency levels, indicating a positive correlation between the efficient use of energy and the ability to meet energy demands with internal production.

The findings of this study underscore the importance of policies supporting the development of PEDs as a substantial way to contribute to reducing energy inequalities, improving access to sustainable energy services, and promoting environmental justice. From the social viewpoint, PEDs can also act as catalysts for greater community cohesion, encouraging citizen participation in sustainability initiatives and raising awareness about the importance of energy efficiency and the use of renewable energy. However, some limitations arise as certain SDG indicators were not assessed due to data unavailability. In addition, despite the promising outcomes, this study focuses on a single district in Italy considered as a potential PED candidate, which, however, does not restrict the generalizability of the findings, given that baseline values have been derived from national data.

The results from the case study, however, also point towards opportunities for improvement. Buildings with lower efficiency and self-sufficiency highlight the need for targeted interventions, such as retrofitting or the adoption of more efficient appliances and systems. By addressing these areas, urban areas can further enhance their contribution to the SDGs.

Further research directions could involve applying the model to a broader range of urban contexts, both in developed and developing countries. Further studies might also explore the interaction between PEDs and other SDGs not considered in this study, as well as analyze the long-term impact of PEDs on urban and social dynamics.

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