Review Article

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Special issues in assessing a positive energy district as a part of sustainable development

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Abstract— The Positive Energy District (PED) concept is integral to achieving Global Sustainable Goals, representing a crucial component of comprehensive sustainability efforts. This work delves into specific issues that are infrequently addressed but hold significance to PED projects or may exhibit correlations with other performance indicators. These include discussions on "green infrastructure," "waste utilization," "energy and emission footprints on household level," "farmland usage," and the composite indicator "quality of life per greenhouse gas emission." Each topic is examined within the context of its conventional understanding, and the primary approaches for studying them are elucidated.

Keywords: positive energy districts; greenhouse gas emission; waste utilization; green infrastructure; urban farming.

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I. INTRODUCTION

Sustainable development stands as a contemporary imperative, drawing significant attention from the global community. A cornerstone of this endeavor, as evidenced by various studies, is the imperative of energy decarbonization [1], [2]. Within this context, urban areas are receiving heightened scrutiny.

Urban energy systems are at a critical juncture, necessitating transformation to achieve decarbonization objectives while fostering cities that are more efficient, adaptable, and self-sustaining. Given that cities are substantial contributors to global carbon emissions, they represent ideal arenas for developing and implementing ambitious decarbonization strategies [3], [4], [5]. Current efforts to overhaul urban energy systems are unfolding through diverse experimental setups such as urban, living, and transition labs [6], alongside dedicated testbeds [7], [8], [9].

Positive Energy Districts and neighborhoods (hereafter referred to as PEDs) offer a compelling approach to reshaping energy production, distribution, and consumption dynamics. By concentrating efforts within delineated and manageable spaces, PEDs facilitate swift and comprehensive transformations, thereby contributing to the attainment of decarbonization targets [10], [11].

However, effecting meaningful changes to energy systems demands not only technical and economic expertise but also active engagement from stakeholders embedded within these systems. The effective orchestration of these components, guided by relevant methodologies, is paramount for successful PED assessment. Despite the abundance of available studies and described methods in them, a comprehensive examination of PED characterization and assessment is associated with several difficulties. Their identification and coverage of existing solution methods is the task of this review.

II. PROBLEM FORMULATION

The process of PED realization requires evaluation criteria, which are usually called Key Performance Indicators (KPIs). The wide spectrum of KPIs developed and associated with PEDs [12]. However, some conceptual issues are still not solved.

The objective of this paper is to identify specific issues poorly considered in the PED context, emphasizing their relevance and importance in achieving sustainable PED implementation and highlighting the existing approaches to solving mentioned issues. By focusing on these underrepresented aspects, this study aims to bridge the gaps in existing research and offer insights into their critical role in fostering environmental sustainability and enhancing the quality of life in urban areas.

III. METHODOLOGY

In general, the methodology for achieving the stated objective is as follows (Fig. 1). The process flow diagram is represented in BPMN notation [13], [14] and consists of three main tasks: analysis of the PED aspects; identification of the poorly considered PED aspects; and the highlighting of existing approaches for their implementation.

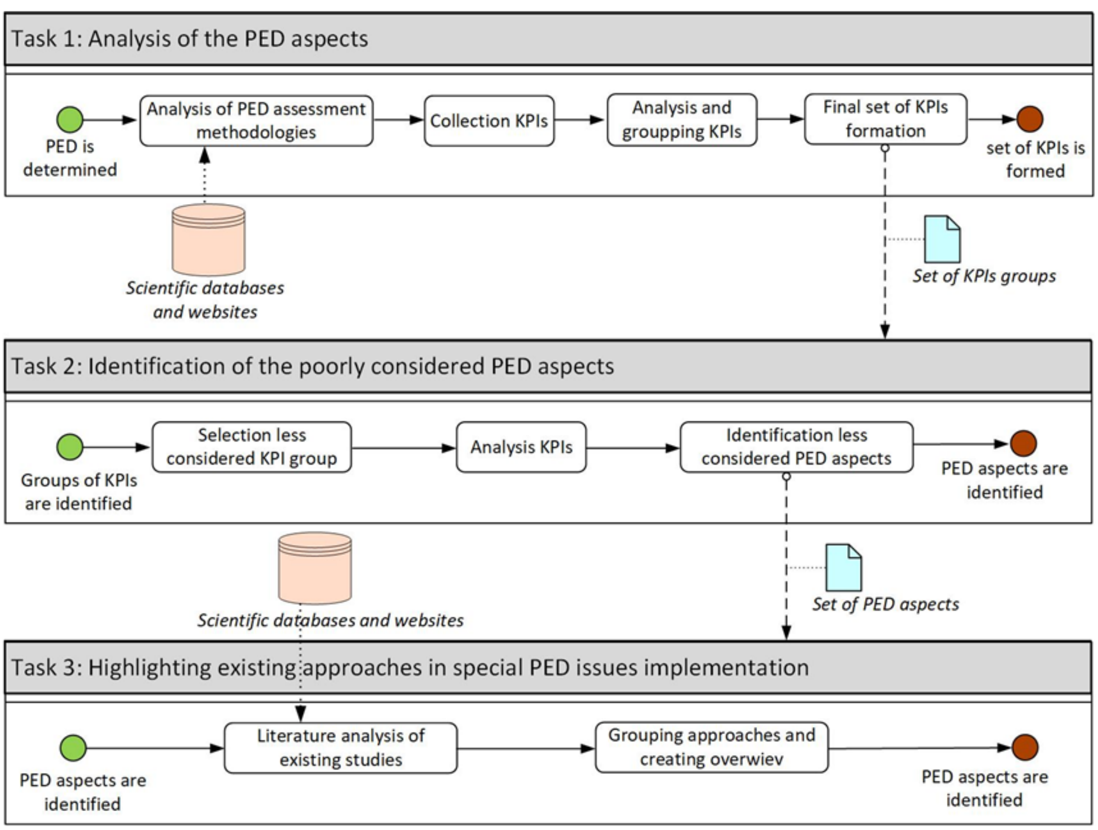

Figure 1: Process flow diagram of the applied methodology.
Source: Own elaboration.

A comprehensive literature review (partially presented in [15]) identified six primary categories of KPIs relevant to Positive Energy Districts (PEDs):

- The Technical category encompasses all KPIs related to the technological and infrastructural aspects of PEDs, such as energy supply and demand, the efficiency and performance of installed equipment, and system reliability.
- The Environmental category includes KPIs that assess the ecological impact of PEDs, focusing on factors like carbon dioxide emissions, noise pollution, air quality, and resource efficiency.
- The Economic category addresses financial considerations, covering KPIs related to costs, investment returns, and economic feasibility assessments.
- The Social category includes KPIs that capture public perception, social acceptance of energy transitions, and community engagement in PED projects.
- The Information and Communication Technologies (ICT) category covers indicators related to the integration and application of digital technologies in PEDs, such as smart monitoring, control systems, and data management for optimizing energy flows.
- The Legal category encompasses KPIs that evaluate regulatory and institutional frameworks, including compliance with laws, policies, norms, and both formal and informal governance structures.

It is evident that the wide range of parameters used to assess PEDs, commonly referred to as KPIs in the literature, reflects their key aspects. The greater the number of KPIs assigned to each individual component of a PED, the more thoroughly and comprehensively it is analyzed by researchers.

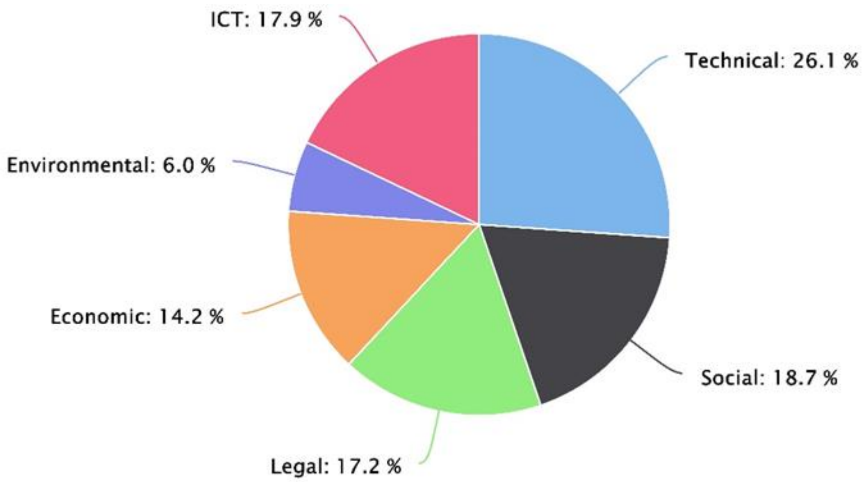

Figure 2: KPIs representation by categories.
Source: Own elaboration.

Figure 2 illustrates the distribution of KPIs across different categories in the reviewed literature. The analysis indicates a relatively balanced representation of KPI types. While technical and social-related indicators are more prevalent, the dataset covers a broad spectrum of topics and objectives, enabling a holistic assessment of PED performance. However, environmental issues receive comparatively less attention.

The Environmental KPIs could be classified into 10 sub-groups (Fig. 3): Green Infrastructure; Waste Utilization; Energy and Emission Footprints on Household Level; Farmland; Quality of Life per Greenhouse Gas Emission; Water Resource Management; Air Quality; Pollution Control; Sustainable Transportation and Mobility; Climate Resilience and Adaptation.

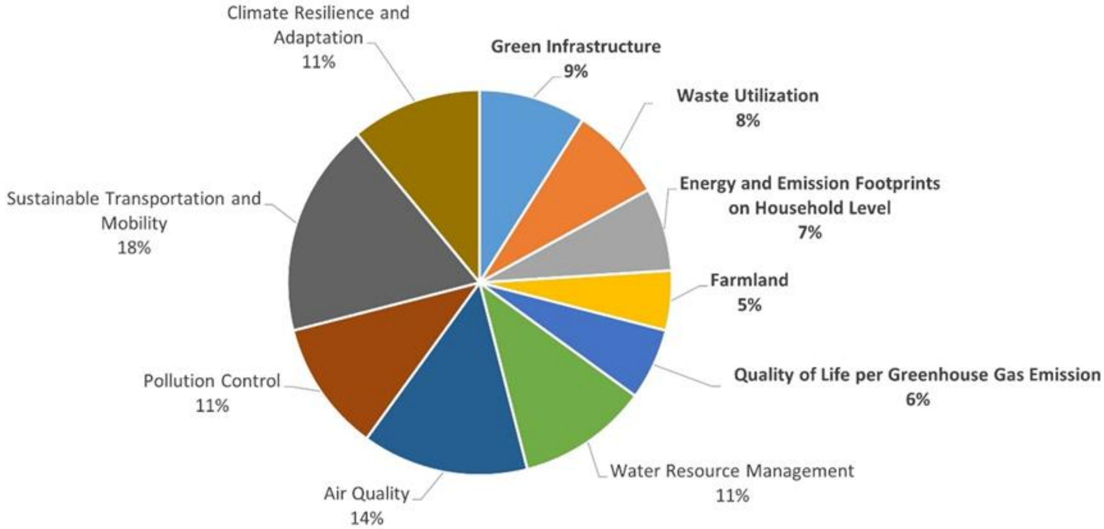

Figure 3: Sub-groups of environmental KPIs.
Source: Own elaboration.

Some sub-groups of environmental KPIs, such as Farmland, Quality of Life per Greenhouse Gas Emission, and Energy and Emission Footprints on Household Level, likely receive less attention in PED research due to the need for detailed and localized data collection, which makes standardization across different PEDs challenging. Additionally, some of these aspects may not be considered immediate priorities in PED development.

The following section provides an overview of the five least-examined aspects of PEDs and existing approaches to studying them.

IV. KEY ISSUES IN PED ASSESSMENT

a. Green infrastructure

Green infrastructure plays a crucial role in urban planning and development [16], particularly in mitigating energy demands within cities [17]. Its absence not only diminishes the quality of life but also exacerbates environmental pollution, presenting a significant hurdle to effective PED implementation. However, assessing and evaluating green infrastructure poses considerable challenges, with limited representation in existing literature.

An article [18] addresses this gap by investigating urban distribution patterns using satellite imagery and remote sensing techniques. To assess the distribution of green spaces, the study employs a supervised classification algorithm, specifically the Maximum Likelihood Classifier (MLC), to categorize land surface features. The evaluation of the environmental quality and urban spatial characteristics utilizes the "green area per capita" index. Despite focusing primarily on methods for assessing green spaces, the authors overlook the crucial role of green areas in positive energy districts.

Authors in the study [19] took a significant stride toward assessing green infrastructure within urban ecosystems. They analyzed the urban landscape using a building-oriented method, considering four key parameters: Green Index (GI), proximity to green spaces, building density, and building height. Incorporating building characteristics into the model enhances the effectiveness of this approach for land suitability analysis and urban planning, including within the realm of PED development and implementation.

A similar methodology was previously proposed by authors in the article [20]. They introduced the Building's Proximity to Green spaces Index (BPGI) as a measure of a building's adjacency to green spaces. However, the results indicate that this index is applicable only at the individual building level; its applicability at higher levels (e.g., groups of buildings, neighborhoods, etc.) requires further investigation.

In the study [21], researchers quantitatively examined the utilization of the green space index regarding its impact on environmental pollution. Additionally, they suggested employing five different types of green space indexes to evaluate city zones, aiming to identify promising areas for future development.

In another study [22], authors delved into the dynamics of the green space index, employing metrics such as the Urban Green Space Index (UGSI) and Per Capita Green Space (PCGS). They presented formulas and highlighted the effectiveness of their method, as evidenced by notable performance metrics including mean precision, recall, and accuracy, all of which hold significant importance in PED development.

Some authors have drawn strong connections between the green space index and other key performance indicators (KPIs) of PED. In an article [23], researchers examined the relationship between the green space index and noise levels in urban areas and agglomerations. They asserted that green spaces have consistently shown a positive impact on reducing traffic noise pollution at the local scale.

In the implementation of PED projects, it is imperative to consider not only the technical aspects of green infrastructure but also various other factors such as economic, social, and legal considerations, city ergonomics [24], etc. While social issues were briefly touched upon in the study [25], they were discussed in a predominantly descriptive manner. However, research conducted in [26] sheds light on the economic, social, and environmental benefits of green infrastructure while also presenting a methodology for their evaluation. The authors argue that gaining a clearer understanding of the value of green infrastructure will aid communities in determining where, when, and to what extent such practices should be integrated into future planning, development, and redevelopment efforts. These multifaceted aspects hold relevance for PED projects as well, emphasizing the need for comprehensive analysis and consideration beyond just technical aspects.

In the study [27], green infrastructure is examined alongside the energy efficiency of buildings as a crucial component of the economic considerations in PED implementation. The authors devised a strategy to introduce urban green infrastructure aimed at creating a dual positive impact on cities. This strategy involves both initiating seismic retrofitting and decreasing the cooling energy demand of the current urban infrastructure. The effectiveness of this approach was evaluated across various scenarios involving the acquisition of private land by public administrations, thereby addressing legal aspects of green infrastructure implementation as well.

b. Waste utilization

A cornerstone of sustainable waste management lies in the co-generation of energy and valuable products alongside their responsible disposal. This approach not only generates renewable energy but also operates within a zero or negative carbon cycle, resulting in reduced climatic and environmental impacts [28]. Consequently, the waste-to-energy approach emerges as a highly appealing option for PED initiatives.

In the pursuit of sustainable development, PED implementation necessitates the integration of renewable and eco-friendly energy sources. Within this framework, waste utilization presents a viable avenue for exploration. Article [29] delves into prospective energy utilization patterns, addressing associated environmental impacts, proposing solutions to current environmental challenges, and examining the interplay between renewable energy technologies and sustainable development. The discussion places significant emphasis on waste-to-energy pathways as promising avenues for achieving both environmental sustainability and energy security in PED initiatives.

In a noteworthy study [30], authors introduced an innovative approach that combines the "waste-to-energy" concept with hydrogen production. They highlighted that this integrated system could achieve impressive energy and exergy efficiencies, reaching 32.7 % and 36.6 % respectively, which are notably high for such systems.

It's worth mentioning that the idea of hydrogen production from waste is not novel. Hydrogen is increasingly recognized as a promising energy source, prompting numerous studies exploring its extraction from municipal waste. One of the pioneering instances of "waste-to-hydrogen" technology was documented in the study [31], where a photovoltaic solar cell system was utilized alongside energy derived from waste plants for hydrogen production.

Moreover, the integration of hydrogen production from waste addresses mobility concerns, a significant aspect of PED implementation, as discussed in the study [32]. This convergence of waste-to-hydrogen technology with mobility considerations underscores the multifaceted potential of waste utilization in advancing sustainable energy solutions for urban development initiatives.

Contemporary research predominantly emphasizes the extraction of hydrogen using environmentally sustainable biological methods [33], [34], which play a crucial role in mitigating greenhouse gas emissions.

Authors of the study [35] identified a close relationship between the utilization of organic waste and the overall energy balance. Through an analysis of waste management strategies, they assessed the potential capacity for biogas production and the energy efficiency of associated equipment.

Several research and development (R&D) projects have implemented modern hydrogen production technologies aligned with PED objectives [36], [37], etc. Collaborating partners within these projects explore various facets of hydrogen production, including the development of waste recycling technologies tailored to this purpose.

The concept of "Waste utilization" extends beyond the traditional understanding of waste as materials generated from human activities. Many researchers also explore the notion of "waste heat" as part of this broader topic.

Waste heat refers to the thermal energy that goes unused and dissipates into the surrounding environment during the operation of equipment or other technical systems. Within the context of PEDs, this could include heat emitted from building ventilation systems. Given that Positive Energy Districts aim to maximize energy efficiency, the utilization of waste heat (i.e., increasing the energy efficiency of all components) becomes a critical concern.

A study [38] examined the potential for waste heat recovery, particularly focusing on buildings within a designated district in Finland. The authors identified buildings constructed between the 1960s and 1980s as having significant potential for heat recovery. Renovating these structures could lead to annual reductions in CO_2 emissions. Such findings provide valuable insights for PED strategy implementation, particularly through the revitalization of existing older districts.

The waste-to-energy strategy can encompass actions involving waste heat utilization. In the study [39], authors propose enhancing waste-to-energy plants by integrating waste heat recovery systems. These solutions not only reduce energy consumption but also enhance economic and environmental performance.

The term "waste" is also included in Key Performance Indicators (KPIs) commonly used in PED implementation projects. For instance, the KPI "symbiotic waste heat legal framework compatibility" assesses the legal framework's suitability for integrating symbiotic waste heat solutions. This qualitative criterion addresses legal issues relevant to PEDs, as mentioned by [40]. Additionally, waste heat is referenced in the KPI "Heat Recovery Ratio," which quantifies the percentage ratio of total thermal energy output to thermal energy recovered through waste heat recovery technologies [41].

From an environmental standpoint, KPIs such as "Municipal Solid Waste" and "Recycling Rate of Solid Waste" are significant. The former measures a city's waste production and the level of service provided for waste collection, while the latter estimates the percentage of a city's solid waste that is recycled [42].

In the context of PED implementation, social issues, particularly regarding waste utilization, must be carefully considered [43]. This aspect was thoroughly addressed in [44], where authors highlighted the importance of addressing the "Not In My Back Yard" (NIMBY) syndrome when planning waste utilization infrastructure development. This syndrome poses a significant challenge in Municipal Solid Waste management schemes during PED implementation.

c. Energy and Emission Footprints on Household Level

The Positive Energy District concept is intricately linked to energy demand and CO_2 emissions, typically assessed at the level of city districts, neighborhood districts, or entire cities [45], [46] etc. However, it is equally crucial to consider the household level as a fundamental structural unit shaping the overall energy consumption and emission profile of a city.

Numerous studies have focused on household emissions, often facing the challenge of generalizing household profiles during assessments. To address this, researchers commonly employ reduced coefficients such as CO_2-equivalents per square meter [47], and CO_2-equivalents per capita [48], among others. Nonetheless, the overarching findings suggest that reducing CO_2 emissions can be achieved through strategies such as increasing population density and widespread adoption of low-carbon energy technologies.

Another challenge arises in assessing a large number of households. In the study [47], data from approximately 93 million individual homes were analyzed, employing suitable approximation models. Statistical projections of the "carbon footprint" from households were utilized in the study [49], wherein authors employed a consumption-based accounting framework. They addressed the issue of handling big data through scaling and urban-rural weighting techniques.

Energy and carbon footprints are typically correlated with various types of consumption using multi-regional input-output models, evaluating footprints per unit of expenditure [50]. Various methods of simplification and approximation are employed to derive values at the household level.

In contrast to the aforementioned methods, a "self-assessment" approach is used for households [51]. Authors demonstrated that "self-assessed environmental sustainability" more accurately reflects individuals' attitudes toward the environment compared to footprint calculations. However, this approach may entail a high level of uncertainty, which should be duly acknowledged. While there exist a few online calculators as developments of the self-assessment approach [52], their usage is primarily intended for educational purposes.

The self-assessment approach can be classified as a social scientific method, utilizing methods typical of that discipline [53]. Its effective utilization in PED development and implementation necessitates combining it with methods for capturing footprints based on approximating general data to the household level.

d. Farmland

Urban farming, also known as "farming," though not widely discussed in the literature, holds relevance in the context of PED development. Typically, urban farming refers to the production of food within or near urban areas [54]. While its primary focus is on food production, the utilization of green areas is a fundamental component. Therefore, the development and assessment of green zones and regions within cities will be further explored, addressing issues related to urban farming and green zone usage.

The installation of green roofs (Fig. 4) is a prevalent method for fostering district positivity, with well-known advantages [55], [56]. A study [57] examines the possibility of using these rooftops for farming purposes, highlighting their benefits. The authors emphasize the importance of implementing green roofs for urban purposes, especially in densely populated cities.


Figure 4: Urban farming and green roofs.
Source: https://greenrooftechnology.com.

Social aspects of utilizing urban areas for farming are explored in [58], [59], revealing a strong correlation between this practice and public perception. Informing people about the positive impacts of agricultural space utilization in the context of creating positive energy districts and achieving sustainable goals emerges as crucial.

While the term "farmland" is infrequently used in the context of positive energy districts, urban agriculture contributes to the sustainable development of cities and supports regional food security [60]. This aligns with the broader goals of PED development and implementation. Study [61] delves into the legal aspects of urban agriculture, emphasizing the farmland market as a component of green sustainable strategies in city development.

e. Quality of Life per Green-House Gas Emission

The literature review reveals that a key performance indicator (KPI) within Positive Energy Districts (PEDs), namely "Quality of Life per Greenhouse Gas Emission," is not commonly utilized for assessment. However, this KPI comprises two interconnected sub-terms: "Quality of Life" and "Greenhouse Gas Emission."

"Quality of life" encompasses various aspects of citizens' daily lives, such as health, economic status, resource demands and availability, and psychological well-being. The quality of life can be linked to PED implementation. For instance, considerations of resource availability may include energy requirements for heating, cooling, or daily electricity usage. Achieving a balance between energy demand and supply is a common approach to characterizing PEDs, hence the term "quality of life" may serve as a relevant descriptor.

On the other hand, "Greenhouse Gas Emission" is closely associated with Positive Energy Districts, as the conceptual understanding of PEDs involves reducing greenhouse gas emissions. This concept is extensively explored in studies [62], [63], etc.

Let's delve deeper into how these terms are presented and understood in the scientific literature within the context of PEDs.

Public health emerges as a significant aspect of quality of life. Numerous studies address the impact of transitioning short vehicle trips to walking and cycling on human health and greenhouse gas emissions reduction. For instance, the article [64] tackles this multifaceted issue, proposing solutions that not only mitigate environmental impacts but also yield economic benefits.

Mobility, a crucial aspect of PED assessment and implementation [65], is also scrutinized in the context of quality of life. Research such as [66] explores the effects of implementing electric vehicles on air pollution, highlighting how reducing greenhouse gas emissions and enhancing mobility can enhance citizen satisfaction, health, and overall quality of life.

The implementation of renewable energy technologies, aimed at reducing greenhouse gas emissions, is sometimes intertwined with the issue of energy poverty [67]. Scholars argue that renewable energy offers a swift and effective means to address energy poverty while advancing sustainable development goals. Some studies also consider energy poverty as a significant component of quality of life, positing that insufficient access to energy sources limits daily satisfaction of basic needs [68]. This association between energy poverty and quality of life underscores the importance of addressing economic poverty and implementing sustainable energy strategies [69]. However, the correlation between energy poverty and greenhouse gas emissions has not been extensively studied, as evidenced by the lack of literature in existing scientific repositories.

V. CONCLUSIONS

In conclusion, the pursuit of sustainable development has become a focal point for the global community, with energy decarbonization emerging as a primary objective. Urban areas, being significant contributors to global carbon emissions, are increasingly under scrutiny for transformation. Positive Energy Districts (PEDs) offer a promising avenue for reshaping energy dynamics within urban environments, providing a framework for rapid and comprehensive transformation toward decarbonization goals.

Among the wide range of possible aspects by which a Positive Energy District (PED) can be assessed, six main categories have been identified: Technical, Environmental, Economic, Social, Information and Communication Technologies (ICT), and Legal. Among these, the Environmental category is the least frequently considered in research. To address this gap, an in-depth analysis of existing environmental KPIs was conducted, leading to the identification of five of the least-examined aspects: Green Infrastructure, Waste Utilization, Energy and Emission Footprints on Household Level, Farmland, and Quality of Life per Greenhouse Gas Emission.

Green infrastructure, waste utilization, energy and emission footprints on the household level, farmland integration, and quality of life per greenhouse gas emission emerge as critical areas for consideration in PED implementation. In addressing these challenges, it is imperative to adopt a multidisciplinary approach that considers technical, economic, social, and legal dimensions. Collaboration among stakeholders, including policymakers, urban planners, engineers, environmental scientists, and community members, is essential for navigating the complexities of PED development and implementation.

The most effective methods for assessing Green Infrastructure in the context of Positive Energy Districts include the use of green space indices, urban planning that incorporates green areas while considering building density, and other related approaches. The most accurate evaluations are achieved through a comprehensive approach that integrates technical, environmental, and socio-economic analysis methods.

Promising methods for developing the aspect of waste utilization in the context of PED include integrating waste-to-energy technologies with hydrogen production, utilizing organic waste for biogas production combined with assessing energy efficiency in waste management systems and recovering waste heat in older buildings, particularly through renovations.

The most effective methods for estimating Energy and Emission Footprints at the household level in the context of Positive Energy Districts (PED) are combined approaches that integrate statistical, econometric, and social methods to provide the most accurate assessment of energy consumption and CO_2 emissions.

At the considering the farming aspect in PED implementation, the most effective methods for assessing urban farming are those that integrate environmental, social, and legal factors, facilitating its incorporation into PED development and sustainable urban planning.

When considering the aspect of Quality of Life per Greenhouse Gas Emission in PED implementation, the most effective and widely used methods are those that simultaneously reduce greenhouse gas emissions and enhance quality of life. These include the development of sustainable transportation, the adoption of renewable energy sources, and the integration of socio-economic factors into PED planning.

Moving forward, further research and innovation are needed to advance our understanding of PEDs and to develop robust methodologies for their assessment and characterization. By leveraging the insights gained from this review and building upon existing knowledge, we can pave the way for the widespread adoption of PEDs as a transformative tool for sustainable urban development.

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