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Linking environmental impact assessment and Positive Energy Districts: A literature review

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ABSTRACT

This research delves into the environmental impact assessment of Positive Energy Districts (PEDs), focusing on comparative analyses of methodologies, key performance indicators, and an array of both theoretical and practical case studies. The literature review uncovers the strengths and weaknesses inherent current evaluation practices. The study reveals critical gaps in current assessment frameworks, particularly regarding the application to PEDs. It highlights the necessity for a holistic approach to PED evaluation, incorporating diverse energy sources and consumption patterns to fully understand their impact. The research advocates for the integration of multiple environmental factors in terms of innovative design and technology in PEDs, tailored to enhance both functionality and sustainability. It calls for the development of standardized guidelines and the learning from successful implementations to ensure the resilience and effectiveness of PEDs over time. Thus, this review paper aims to contribute to the body of knowledge on PEDs, offering insights and recommendations for future developments in this critical area of sustainable urban and energy planning.

1. Introduction

In an increasingly globalized world, cities serve as key communication centers and consume over two-thirds of global energy, making them the primary contributors to climate change and crucial players in preventing its most severe impacts. To achieve the clean energy transition required for the Net Zero Scenario by 2050, the carbon footprint of cities and buildings must be reduced by more than half by 2030. Hence, significant efforts are needed to lower energy consumption using renewable-based technologies and high-efficiency solutions (IEA, 2022). The essential contribution of cities to the energy transition is broadly recognized. It serves as a fundamental element of global agreements aimed at promoting sustainable development, such as the New Urban Agenda (New Urban Agenda) and the European Green Deal, in which the European Union (EU) launched the “Renovation Wave” initiative, seeking to improve the renovation of buildings and targeting the refurbishment of approximately 35 million buildings units by 2030 (European Commission, 2020).

Nevertheless, it is widely known that expanding the scope of building-level strategies is essential. These approaches hold significant

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potential for accelerating the reduction of greenhouse gas emissions in the building sector. They also enable leveraging interactions among various buildings and optimizing the integration of renewable energy sources (European Commission, 2019).

Thus, to address these challenges, various concepts have emerged, including smart cities, zero energy districts, zero carbon neighbourhoods, net-zero energy communities, and Positive Energy Districts (PEDs). While these concepts share similar goals, PEDs stand out by aiming to generate more energy than they consume.

PEDs have emerged as a promising model fostering the transition towards more sustainable, resilient and affordable urban settlements and are being developed as essential components for energy-efficient environments, aligning with international sustainable development agreements. PEDs embody the principles of self-production, self-consumption, and zero emissions, showcasing a transformative approach to urban energy use, as well as deal with social inclusiveness, stakeholders' involvement and economic aspects. In addition, being innovative urban areas characterized by a positive energy balance, PEDs inherently prioritize sustainability, energy efficiency, sustainable mobility and the use of renewable resources. However, PEDs cannot be reduced to mere technical systems with a high level of innovation, still are to be considered complex systems that cover various and interlinked dimensions of sustainability aspects, governance, urban planning and dimension, to mention few of these.

Originating from the smart city initiative, PEDs gained momentum with the European Commission launching the PED Programme in 2018, later revised with targets up to 2030. Despite being in early stages, with only 3.5% realized as of 2020, PEDs offer valuable insights for ongoing projects. Successful PED projects adopt a holistic perspective, integrating various elements such as energy generation, efficiency, mobility, and social factors to achieve optimal energy performances. Due to their crucial role in the European Union's climate and energy strategies, PEDs are gaining global recognition. Initiatives as the "Clean Energy for All Europeans" package, the Action Plan 3.2 of the European Strategic Energy Technology Plan (SET-Plan) (European Commission), and the International Energy Agency (IEA), Energy in Buildings and Communities (EBC) Annex 83 (International Energy Agency (IEA)) dedicated to PEDs aim to facilitate collaboration among stakeholders and unlock the full potential of PEDs.

Implementing PEDs within cities faces diverse and intricate challenges due to their novelty and lack of practical experience. In addition, similarly to the concept of smart cities, PEDs encounter scepticism and challenges due to the absence of a unified and precise definition. This ambiguity affects their initiation, planning, and implementation. The lack of a comprehensive terminology useful for a systematic approach drives the need for appropriate methodologies and tools tailored to the urban-scale analysis of districts. It is worth clarifying that, the absence of a clear definition is not a direct consequence of discouraging investments, still it is unquestionable how financial, regulatory and systemic barriers play a critical role in implementation delays. Furthermore, linking PEDs with the environmental impact assessment may result in a strategic approach to enhance their diffusion while minimizing their environmental impacts. Indeed, by integrating the environmental impact assessment into the planning, development, and operation phases of PEDs, stakeholders not only can ensure the achievement of energy-positive goals but also contribute positively to the environmental, social, and economic sustainability goals of their surroundings.

Several researchers have focused their attention on PEDs, and various review papers have been developed to address their challenges. Koutra et al. (2023) aimed to identify the key aspects and areas lacking in existing literature concerning methods for creating positive and self-sufficient districts, considering diverse challenges such as urban and social issues. In essence, the review offers a thorough analytical examination of how the conception and design of PEDs emphasize the significance of comprehensive and community-focused approaches for establishing sustainable and self-sustaining communities. Sassenou et al. (2024) offered a comprehensive overview of the progress in research on PEDs, emphasizing applied studies and real-world experiences. Natanian et al. (2024) presented a comprehensive framework comprising questions pertinent to the design of PEDs, integrating a diverse range of tools and methodologies, emphasizing the need for innovative methodologies and tools to foster robust, resilient, and data-informed processes within the dynamic, multi-scale, and interdisciplinary urban landscape.

All the previous useful review articles focus on general theoretical or methodological aspects related to PEDs, highlighting the benefits of these types of user aggregations and the challenges to overcome for their implementation. However, a systematic review focused on one of the main positive impact of the diffusion of PEDs, namely the reduction of the environmental impact of cities, has never been conducted.

This review aims to compile the main methodologies, often interconnected, used for assessing environmental impact on an urban scale, highlighting the challenges yet to be overcome in this field and the pros and cons of the applicability of each methodology. This study is intended to offer to the scientific community a comprehensive understanding of the adopted methodologies, with the goal of eventually defining a standardized methodology for assessing the environmental impact of PEDs. The standardization should not be intended as a rigid method that must be universally applied, regardless of the context, dimensions and peculiar aspects of any PED. On the contrary, standardized approaches enable the definition of consistent frameworks that give practitioners the chance to compare results and permit decision-making across different projects, share best practices, permit replicability and avoid misinterpretations of environmental outcomes. This is also the direction of international standards and of methodological approaches, such as the LCA, applied to various and heterogeneous fields, from buildings to industries. In this sense, standardization helps establishing guidelines that do not eliminate differences rather offer flexibility, allowing project to account for their specific nature while adhering to environmental assessment principles.

As a further remark, although the scope of this paper is oriented to the environmental assessment of Positive Energy Districts, is it worth mentioning that PEDs are also strictly connected to the aspects of i) integrated and ii) development of innovative business models (European Commission). The core of the first aspect highlights that PEDs are, accordingly, not only connected to technological innovation (and implicitly achieving a mere positive mathematical energy balance), but they need to strive to fight e.g. energy poverty and social vulnerabilities in an integrated approach (Natanian et al., 2024). The second element is motivated by governance considerations, namely the interplay of authorities, investors/business units and residents/households. PEDs should realize a balance between the envisioned goals regarding environmental impact, social inclusiveness and business innovation. The following sections will investigate prominently the environmental aspect but all three aspects mentioned are needed in a complete sustainability assessment.

2. Theoretical framework

The methodology implemented for conducting the state-of-the-art analysis involved searching publications in the Scopus database (Burnham, 2006). This was achieved by utilizing various query strings, as detailed in Table 1. The first two queries yielded 669 and 623 documents, respectively. However, when the search was refined with additional details (as in query 3), only 144 documents were retrieved.

An analysis of the initial data indicated a significant and rapid increase in interest regarding the topic of environmental impact assessments at the district scale. This growing trend is clearly depicted in Fig. 1, which shows a substantial rise in the number of related publications during the period from 2015 to 2024. Specifically, the search results reveal a notable growth in academic attention: while only four

Table 1
Query strings in Scopus database.

	Query	Documents
Query 1	TITLE-ABS-KEY (zero AND energy AND districts)	669
Query 2	TITLE-ABS-KEY (zero AND energy AND neighborhood)	623
Query 3	TITLE-ABS-KEY ((“Positive energy district” OR “Zero energy district” OR “solar districts” OR “smart district”) AND (“Environmental” OR “sustainability”))	144

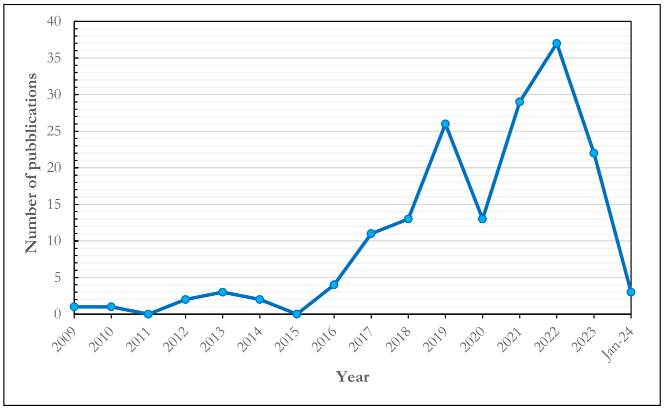


Fig. 1. Number of publications per year for query 3, year 2009–2024.

papers on the topic were published in 2016, this number escalated to 37 by 2019.

Furthermore, Fig. 2 illustrates that the publications identified through query 3 are unevenly distributed across various types of publication typologies. Specifically, 57% of the literature reviewed consists of journal papers, making it the most prevalent category. This is followed by conference proceedings, which account for 32%, and reviews, representing 6% of the total. Book chapters and editorials comprise a smaller fraction, covering only 4% and 1% of the literature, respectively.

Based on the reviewed researches, a keyword co-occurrence network was generated, as shown in Fig. 3. It is a graphical representation of relationships between keywords in a dataset, typically used in text analysis and information retrieval. This type of network helps to visualize how often keywords appear together within a set of documents, such as scientific papers or any textual data. After collecting research papers, keywords are identified with the articles, and the next step is to determine how often each pair of keywords appears together within the defined paper collection. Nodes are then created for a unique keyword and they are sized based on the frequency of a specific keyword’s use – the more frequently a keyword occurs, the larger its node. Additionally, the colours of the links indicate the timing of the node connections: blue links represent older connections, while yellow links indicate the most recent ones. The central node “*zero energy buildings*”, “*energy efficiency*”, and “*energy utilization*” are highly connected to many other keywords; thus, they represent central themes in the dataset and, based on their colours, they also are the most recent concepts in PED context. Nevertheless, a high number of co-occurrences is recorded for the keyword “*sustainable development*”, even if in this case the edges’ colours indicate less recent occurrences. The isolated and/or smaller nodes represent keywords with few connections, being niche topics or emerging areas of research.

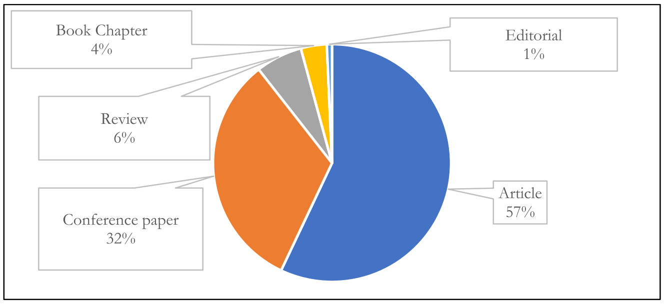


Fig. 2. Type of the reviewed literature for query 3.

As shown, only in recent years the life cycle perspective has been associated with the concept of Net Zero Energy Buildings (NZEBs), indicating a growing interest from the scientific community and the need for further efforts in the field of life-cycle assessment (LCA) and eco-design of innovative urban concepts, such as NZEBs. In fact, for sustainable development objectives to be achieved, it is essential that high-efficiency urban concepts are not only assimilated to mere energy innovation hubs following a purely technocratic approach. On the contrary, such building concepts are potentially bulwarking of sustainability centered on the combination of technical and energy innovation tools and elements of environmental, social and economic sustainability. However, the bibliographic analysis shows how further research efforts are required from a methodological point of view for the demonstration and diffusion of eco-design practices of emerging building concepts. As can be seen, keywords such as “*positive energy*” and “*Positive Energy Districts*” have not been found, indicating in particular the need to investigate in more detail the correlation between Positive Energy Districts and environmental sustainability, also evaluated in terms of embodied emissions following an LCA prospect. Among the aspects of environmental sustainability, attention has recently been paid not only to carbon emissions but also to other categories of environmental impact and evaluation criteria, such as air pollution. This is fundamental in order to avoid shifting impacts from one category to another and to define fully environmentally sustainable approaches for PEDs. However, a clear and integrated approach to environmental sustainability remains a challenge. The building sector, in particular, faces barriers due to the lack of clear methods and frameworks for evaluating these broader environmental impacts. This gap limits the effective implementation of PEDs and underscores the need for an integrated sustainability perspective (i.e. keyword “*integrated approach*”). An integrated approach can be understood in two ways: horizontally, as the combination of environmental and socio-economic sustainability practices; and vertically, as the development of tailored multi-criteria environmental methods. These themes are analysed in detail and discussed in the remainder of this paper, which aims to highlight the opportunities and challenges, barriers and research gaps that need to be addressed for the definition of a roadmap towards the environmental sustainability of PEDs.

3. Approaches to environmental sustainability assessment for PEDs

PEDs represent an innovative and sustainable approach to urban development, aiming to create districts that produce more energy than they consume through the integration of renewable energy sources and advanced energy efficiency measures. The literature review facilitated an in-depth analysis of the methodologies applied in studying environmental sustainability at the district scale. It was observed that many studies employed multiple methods, with a significant number introducing new methods, frameworks, or tools. Methodologies vary in depth according to the objective and scope of the study, as reported in Table 2. Even though the list of case-studies is not exhaustive of the potential variables characterizing a district, it includes a variability of solutions about the district typology (mixed, residential, non-residential) and of geographical locations within and outside EU. They range from a basic use-stage perspective, typically focusing on the modelling and monitoring of energy use and emissions analysis, to a more elaborate Life Cycle Assessment (LCA) approach. Given this variation, it is crucial to

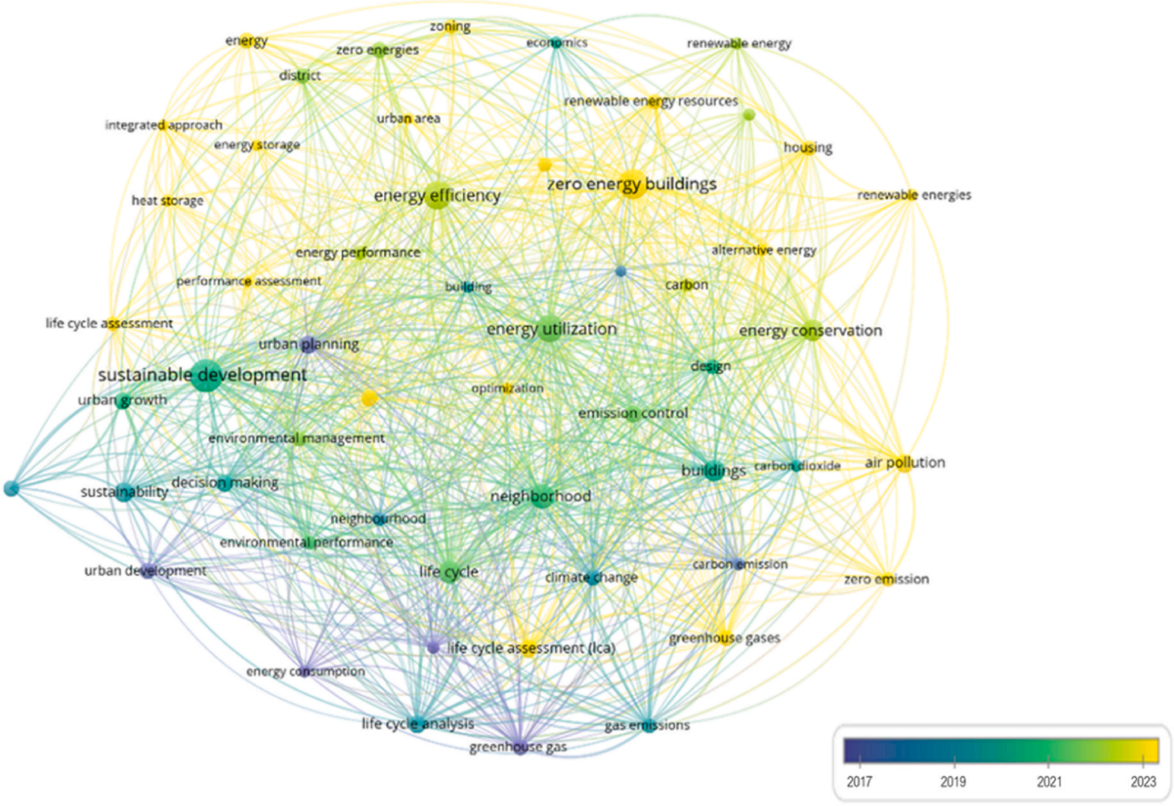


Fig. 3. Keywords co-occurrence network.

Table 2
Overview of main features and methods adopted for the environmental impact analysis of districts.

Country	District use-type	Energy demand		Grid emission factor	RESs-based plants' emissions		Ref.
		Transportation	Waste disposal				
Italy	Mixed	×	×	Constant	Biomass PV	✔ ✔	Volpe et al. (2022)
South-Korea	Mixed	×	×	Constant	×		Kim et al. (2019)
Italy	Residential	×	×	Constant	✔		Haneef et al. (2021)
Italy	Residential	×	×	Constant	×		Aruta et al. (2022)
Finland	Residential	×	×	Constant	×		Hirvonen et al. (2020)
Greece	Residential	×	×	Constant	×		Sougkakis et al. (2020)
Italy	Mixed	×	×	Constant	×		Ascione et al. (2021a)
China	Mixed	✔	×	Constant	×		Xu et al. (2022b)
Switzerland	Mixed	×	×	Constant	×		Sameti and Haghighat (2018)
Sweden	Tertiary	×	×	Constant	×		Wang et al. (2017)
Switzerland	Mixed	×	×	Constant	✔		Orehounig et al. (2014)
Canada	Mixed	×	×	Constant	×		Hachem-Vermette et al. (2016)
Finland	Mixed	✔	×	Constant	×		Paiho et al. (2021)
Belgium	Residential	×	×	Constant	×		Janssens et al. (2017)

explore these two broad methodological domains. This review, therefore, aims to navigate through the range and purpose of methodologies used in the field, emphasizing the importance of exploring both fundamental and comprehensive approaches for the evaluation and optimization of PEDs.

In the operational phase analysis of urban districts, significant strides have been made to broaden the scope beyond energy considerations to include environmental impacts. The adoption of the net-zero exergy approach marks a pivotal shift from traditional analyses based on the first law of thermodynamics to a more holistic view that encompasses both building and district scales (Ahmadi et al., 2021, 2022). This approach integrates environmental constraints by associating exergy efficiency with CO_2 emissions reduction and incorporating additional sustainability indicators, such as those related to urban metabolism (Kılkış, 2017). Such methodologies contribute to bridging the gap in guidelines for designing and analyzing districts with a focus on carbon neutrality at the urban level (Pulselli et al., 2021; Tozer and Klenk, 2019). This section discusses the diverse methods employed in the literature for assessing the environmental performance of districts during their operational phase. It emphasizes the development of a unified framework, highlighting key areas of interest.

- expanding energy demand and emission analysis beyond traditional uses to include urban transportation (Vega et al., 2022) and waste disposal (Del Borghi et al., 2022);
- employing dynamic analysis to monitor the variable operating conditions of districts and their interactions with external power grids

and heating/cooling networks, utilizing precise, time-dependent emission factors (Sartori et al., 2012);
- considering upstream emissions from RES-based plants, which significantly impact the decarbonization of various sectors, including transport (Castillo-Calzadilla et al., 2022).

The analysis of references reveals a noticeable gap in research concerning the energy demand and emissions related to the transport sector, with few exceptions, such as the work of (Xu et al., 2022a). This indicates a broader knowledge gap in incorporating urban transportation into district-level energy and environmental assessments. Similarly, waste management and disposal remain underexplored areas. Despite the mention of potential inconsistencies in the constant emission factor for the power grid by (Hachem-Vermette and Grewal, 2019), the predominant literature tends to overlook the variability of the electricity production mix by assuming constant emission factors. Regarding RES-based plant emissions, there is less consensus, with some studies applying life-cycle emission factors, while others consider these plants as emission-free.

Life cycle-oriented approaches (Guarino et al., 2020; Mastrucci et al., 2020; Lausselet et al., 2019, 2020a, 2020b; Nematchoua et al., 2020; Walker et al., 2018; Lotteau et al., 2015a) at the district scale are applied to a diverse array of urban solutions and processes, including food products (Cerón-Palma et al., 2013), mobility (Lausselet et al., 2021), and both single and multiple buildings. These approaches often extend the scope of environmental impact assessments beyond merely energy and/or GHG emissions, incorporating a more comprehensive range of environmental impacts. The performance of districts during the use stage is typically analysed using a variety of simulation and modelling tools. Some studies integrate these use-stage performance assessments with a life-cycle perspective, offering a more granular analysis of energy demand with high temporal resolution. Conversely, other research focuses solely on operation stage-oriented assessments to gauge the impact of urban planning and building designs on specific energy and performance indicators, particularly in the early design stages.

A notable body of work is dedicated to developing specific modelling procedures for analysing the energy performance of urban areas. Simulation engines such as EnergyPlus (Crawley et al., 2000), Radiance (Compagnon, 1997), and or CFD-based ANSYS CFX (Stolarski et al., 2018) are employed to estimate buildings' energy needs, lighting distribution, and airflows, respectively. At the district scale, specific tools have been devised to model energy flows across the entire city, accounting for the complex interplay between buildings, transportation, energy systems, and other urban elements. These methodologies generally fall into two categories: top-down and bottom-up approaches (Ascione et al., 2021b; Mastrucci et al., 2017). Top-down approaches describe the overall building stock at a macro-level, utilizing statistics or economic schemes-based methodologies (Swan and Ugursal, 2009). This perspective views the district as a clustered entity, providing a general profile of energy demand without delving into the energy characteristics of specific buildings. Here, buildings are considered 'black boxes', limiting the ability to directly assess the environmental impact of building design options or the adoption of passive design strategies and technologies at the building level. Bottom-up approaches, in contrast, focus on the performance of individual components of the building stock, such as specific buildings or technologies, and extrapolate these findings to the broader stock level (Kavgic et al., 2010). This method employs building performance simulations of sets of building representative of actual practice to understand the impact of building design and retrofitting measures on urban-level energy consumption. Some studies, combine multiple models and modelling strategies, coupling simulations of individual buildings with models of district energy plants developed using other specialized tools. Additionally, there are approaches that advance bottom-up building analysis towards more intricate, spatially differentiated models leveraging Geographic Information Systems (GIS) (Mastrucci et al., 2017; Jakob et al., 2013; Fichera et al., 2015, 2016). GIS aids in identifying and visualizing data distributions, supporting decision-making processes at both district and urban scales by managing location-based information and linking databases to spatial maps for dynamic displays. Furthermore, GIS enables the association of buildings with archetypes and the identification of geo-referenced impact sources. Recent research has explored experimental methodologies for evaluating the energy and environmental performance of building stock using GIS alongside regression methods (Torabi Moghadam et al., 2017, 2018), although this spatial analysis has predominantly been conducted at the urban (Nichols and Kockelman, 2014) or regional scale (Reyna and V Chester, 2015). Simulation tools for analysing the energy performance of buildings and districts are built upon a foundation of assumptions and statistical data. Consequently, their predictive reliability hinges on the accuracy of the input data. A notable factor impacting the energy performance of buildings is occupants' behaviour, which can lead to significant discrepancies between actual and modelled performance. Therefore, simulation models should be viewed as analytical tools for relative comparisons between alternative designs and scenarios, rather than as precise indicators of actual performance. Despite their importance, calibration and validation of simulation results are not always performed, though some studies have proposed validation at the building stock level (Tardioli et al., 2020; Allegrini et al., 2015; Talebi et al., 2018). A more detailed validation is required, but the scarcity of monitored data constraints the validation possibilities for these models.

As introduced, the second major category identified in the reviewed studies pertains to life cycle-oriented approaches. The total energy requirements and environmental impacts of buildings go beyond the use phase, incorporating the embodied energy and environmental burdens of building materials and systems from resource extraction and manufacturing to construction, and eventually to dismantling and waste disposal at the end of life. Life Cycle Assessment (LCA) is crucial for identifying potential trade-offs, as life cycle stages are interdependent, with changes in one phase potentially affecting others. For example, choosing building materials to reduce heating requirements could increase embodied energy, impact transportation-related emissions, affect the building's service life, and influence the generation of recyclable or disposable demolition waste. As buildings or districts aim for zero-energy targets, the significance of embodied energy in the building's life cycle becomes increasingly prominent (Paleari et al., 2013; Hernandez and Kenny, 2010). LCA is a comprehensive methodology used to quantitatively assess the environmental impacts associated with all stages of a product's lifetime. It is particularly applicable in the building industry for enabling a detailed analysis of the energy and environmental impacts of products across their entire life cycle, thereby guiding eco-design and informing sustainable design decisions. LCA is standardized internationally (ISO 14044, 2006; ISO 14040, 2006) and typically comprises four stages.

1. *Goal and scope definition*, establishing the analysis's purpose, the functional unit for analysis, and the system boundaries, including spatial and temporal considerations and impact assessment methods;
2. *Life Cycle Inventory Analysis (LCI)*, collecting and quantifying data on energy and material inputs, emissions, waste, and other environmental outputs;
3. *Life Cycle Impact Analysis (LCIA)*, characterizing and aggregating system inputs and outputs to assess their environmental significance;
4. *Interpretation*, summarizing the results from LCI and LCIA, evaluating their quality and drawing conclusions and recommendations.

Detailed literature on the LCA of buildings and building components exists and is the subject of several reviews (Mastrucci et al., 2020; Anand and Amor, 2017; Cabeza et al., 2014; Sharma et al., 2011). However, literature on the application of LCA at the district level faces additional challenges due to increased system complexity and data quality and availability issues, leading to diverse approaches in LCA modelling

(Baynes and Wiedmann, 2012; Finnveden et al., 2009). Table 3 shows literature-reviewed studies that use the LCA methodology to investigate environmental sustainability at the district level and the main assumptions used, such as the functional unit (FU) and the system boundaries. The FU provides a quantification of the identified function of the studied system and constitutes a reference to which the inputs and outputs are related (ISO 14044, 2006; ISO 14040, 2006). A range of FUs has been used, including absolute, spatial (per unit of area), or occupancy-based (per capita). Moreover, FUs are not always explicitly specified in the studies. Generally, the choice of the FU seems to be dependent on the objectives and the presentation of the results. In LCA, the selection of FUs and the precise delineation of system boundaries emerge as pivotal factors. These elements are foundational not only for the interpretation of LCA results but also for facilitating meaningful comparisons across various case studies, technological measures, and interventions. The delineation of system boundaries, in particular, is crucial as it considerably influences LCA outcomes by defining the scope of inclusion for the analysis (Baynes and Wiedmann, 2012; Finnveden et al., 2009). Research varies in focus; some studies concentrate on building clusters, while others extend their analysis to encompass aspects of mobility. The most comprehensive LCAs integrate a broader spectrum of urban elements, including building, mobility solutions, and infrastructural components like open spaces and utility networks. For instance, an examination of the literature summarized in Table 3 reveals that transportation is considered in approximately 85% of the studies, yet fewer delve into the complexities of district-level energy systems or the nuances of urban open spaces, such as roads, bicycle lanes, sidewalks, outdoor parking areas, and public lighting systems. The coverage of each domain differs significantly across studies, with the inclusion or exclusion of specific physical elements tailored to the unique objective of each investigation. The scope of life cycle stages also varies: predominantly, studies incorporate the operational phase, often highlighting the environmental impacts associated with thermal energy demands for heating and cooling. However, the end-of-life phase is considered to a lesser extent – about the 65% of the studies reviewed in Table 3 account for it. The omission of this stage in certain analyses is frequently attributed to data scarcity, the challenges of accurately modelling future demolition and waste treatment processes, and the relatively minor contribution of this phase to the overall lifecycle energy demands and environmental footprints of urban structures. A focused examination of environmental impact indicators in most studies reveals a tendency to concentrate on Global Warming Potential (GWP) and energy demand, particularly emphasizing primary energy requirements. These indicators are often prioritized due to their direct relevance to the objectives of current national and international policies in the realm of built environment sustainability (Mastrucci et al., 2017). Nonetheless, these indicators represent just a fraction of the potential environmental impact categories that could be considered at city or larger scales. Indeed, LCA, by its nature, should provide a comprehensive overview of environmental impacts, shedding light on potential shifts in environmental burdens. European standards such as EN 15643-2 ‘Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance’ and EN 15978 ‘Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method’ recommend a broad array of impact categories for the LCA of buildings, including, but not limited to, acidification potential, and photochemical ozone creation potential (B. S. EN, 2012; European Committee For and Standardization (CEN), 2011). Other scholars have broadened the scope of impact categories further, incorporating considerations related to land use, water scarcity, air pollution, and waste management (Ortiz et al., 2009). Finally, the application of LCA to the environmental impact assessment of districts introduces complex challenges related to the temporal dynamics of urban systems. The interplay between foreground processes (immediate, direct impacts) and background processes (broader, systemic impacts) adds layer of complexity, particularly when forecasting the long-term environmental effects of district-level interventions. The protracted lifespan of urban infrastructures amplifies these challenges, introducing significant uncertainties tied to future energy mixes, technological advancements, and the evolving dynamics of infrastructure and mobility (Lausselet

Table 3

Selection of LCA studies at district scale: overview of main features and methodological choices (Cons. is abbreviation for Construction, Oper. is abbreviation for Operation, Main. is abbreviation for maintenance, Decon. is abbreviation for Deconstruction).

Country	District Type	Boundaries	Number of case studies	FU	LC stages	Ref.
Norway	Residential	Buildings, mobility and energy systems	1	District; m^2 heated floor area; inhabitant.	Cons., Oper.	Lausselet et al. (2020a)
Norway	Mixed uses	Buildings, open spaces, mobility and energy systems	1	District	Cons., Oper. Main.	Lausselet et al. (2019)
Canada	Residential	Buildings, mobility and energy systems	2	Inhabitant; m^2 of living space/inhabitant	Cons., Oper., Decon.	Norman et al. (2006)
Belgium	Mixed uses	Buildings	2	District; inhabitant; per m^2; dwelling unit	Cons., Oper., Main., Decon.	Nematchoua et al. (2019), (2020)
France	Mixed uses	Buildings, open spaces and mobility	1	Year * user	Cons., Oper.	Lotteau et al. (2015a)
Norway	Mixed uses	Buildings, mobility and energy systems	1	District	Cons., Oper., Main., Decon.	Lausselet et al. (2021)
Australia	Residential	Buildings, mobility and energy systems	1	km^2 district; inhabitant	Cons., Oper.	Stephan et al. (2013)
Switzerland	Mixed uses	Buildings and mobility	1	m^2 of energy reference area	Cons., Oper., Decon.	Riera Pérez and Rey (2013)
France	Mixed uses	Buildings, mobility and energy systems	1	District	Cons., Oper., Decon.	Colombert et al. (2011)
Germany	Mixed uses	Buildings, mobility and energy systems	2	District	Cons., Oper., Decon	Herfray (2011)
France	Residential	Buildings	1	District	Cons., Oper., Decon.	Cherqui (2005)
France	Mixed uses	Buildings, mobility and energy systems	1	District	Cons., Oper., Decon.	Peuportier et al. (2006)
USA	Residential	Buildings, mobility and energy systems	4	Per m^2	Cons., Oper.	Nichols and Kockelman (2014)
France	Mixed uses	Buildings, mobility and energy systems	1	District	Cons., Oper., Decon	Peuportier and Roux (2013); Herfray (2011)
Germany	Mixed uses	Buildings, mobility and energy systems	2	District	Cons., Oper., Decon	Peuportier and Roux (2013); Herfray (2011)

et al., 2019; Stephan et al., 2013; Lotteau et al., 2015b). To navigate these uncertainties, some studies have adopted dynamic LCA models that accommodate temporal variations in electricity generation or have constructed scenarios to anticipate future technological developments (Peuportier and Roux, 2013; Herfray and Peuportier, 2010). Unlike static models, which capture a momentary snapshot of the building stock, dynamic models endeavour to trace the evolution of the urban fabric over time, thereby offering insights into the long-term implications of these changes.

Beyond the primary scopes of sustainability assessments discussed previously, additional dimensions often extend to a more integrated sustainability evaluation, incorporating diverse aspects.

- Multi-Criteria Decision Analysis (MCDA) (Hachem-Vermette and Grewal, 2019; Riera Pérez and Rey, 2013; Becchio et al., 2018; Moroke et al., 2019; Neves and Leal, 2010);
- Certification schemes (Tam et al., 2018; U. S. G. B. C. USGBC, 2018; Gelder et al., 2018).

MCDA represents a sophisticated and increasingly adopted approach for aiding decision-makers in navigating the complexities of decision-making in an organized and intuitive manner (Mastrucci et al., 2020; Ortiz et al., 2009; Brøgger and Wittchen, 2018). These methodologies are particularly adept at comparing various solutions by considering a multitude of factors and criteria (Crawley et al., 2000; Li et al., 2017), making them invaluable tools for sustainability assessment at the urban or district level. Here, the intricate range of environmental, social, and economic considerations, coupled with often competing objectives, necessitates careful trade-off analysis. Despite the variety within MCDA methodologies, they share common elements: a set of alternatives, a range of decision criteria, and one or more decision-makers or stakeholders. MCDA is geared towards simultaneously accounting for various qualitative and quantitative aspects, highlighting the perspective of all actors involved (Becchio et al., 2018; Bottero, 2015). The fundamental premise is that complex analyses can be broken down into simpler criteria for separate evaluation, a principle particularly resonant in environmental impact assessments where synthesizing multifaceted information into a coherent form is crucial. MCDA methodologies vary, including (Sharifi and Murayama, 2014).

- Performance aggregation-based approaches, synthesizing information into a single parameter;
- Comparative methods, assessing if 'alternative a is least as good as alternative b';
- Decision rule-based methods.

Building on MCDA foundations, several certification schemes have been devised to evaluate the environmental performance of districts. These schemes often indirectly aim to enhance district environmental performance through sustainability design credits (e.g., solar photovoltaics, enhanced insulation, energy efficiency measures), waste management/recycling, and accessibility to public transportation. Prominent schemes include LEED – ND, BREEAM Communities, and DGNB for Districts, which have been extensively reviewed and compared (Tam et al., 2018; Koutra et al., 2018; Kaur and Garg, 2019; Sharifi and Murayama, 2013). The structure of these systems varies, complicating comparative analysis. Nonetheless, they share a similar framework: themes, criteria, and indicators (Tam et al., 2018). Themes address broad sustainability topics, criteria represent strategies or solutions for these topics, and indicators provide detailed specifications for each strategy. For instance, 'resource and environment' as a theme may encompass 'energy' as a criterion, measured by indicators like 'the district's annual energy consumption' (Sharifi and Murayama, 2013). Various studies have highlighted a skewed focus within these tools towards environmental dimensions, somewhat neglecting socio-economic and institutional aspects. However, an environmental emphasis does not guarantee comprehensive coverage of all environmental issues. For example, analyses of LEED-ND and BREEAM Communities have pointed out gaps in addressing environmental impacts related to GHG emissions, hazardous materials, and natural resource management (Sharifi and Murayama, 2013, 2014; Sharifi et al., 2021; Komeily and Srinivasan, 2015). Table 4 outlines available assessment frameworks for certifying the sustainability of district re (design) initiatives. According to Sharifi and Murayama (2013), district sustainability assessment frameworks fall into two categories: third-party assessment tools derived from building assessment tools, extending sustainability evaluations beyond individual buildings (e.g., LEED – ND, BREEAM Communities and Green Star Communities), and tools integrated into neighborhood-scale plans and sustainability initiatives for assessing their sustainability performance e.g., HQE2R (Blum, 2022), Ecocity, EcoDistricts.

Thus, as emerged, the literature reveals a significant diversity in system boundaries and methodological assumptions, which poses challenges to the interpretation and comparability of results across studies. In certain instances, the quantitative metric under evaluation corresponds to the entire district area, while in others, it pertains to the walkable area of the built environment, sometimes presented on an annual basis or simply as a cumulative emission figure. The system boundaries vary, distinguishing among facilities and aspects of the district (e.g., onsite energy supply systems, buildings, mobility, impact allocation), as well as the life cycle stages included.

4. Key performance indicators (KPI)

KPIs play a crucial role in monitoring and evaluating the implementation, performance and sustainable impact of PEDs. Well-defined KPIs assists in tracking the environmental performance of PEDs and provide a foundation for urban planners and policymakers to develop energy plans aimed at enhancing urban liveability in future scenarios. The identification and discussion of KPIs reported in the following are based on a comprehensive review of scientific literature, reports and standards. Given the diversity and volume of KPIs, nine main macro-areas of application have been delineated.

- *Climate change*, focusing on urban air quality, temperature levels, acidification, precipitation in specific districts, GHG emissions rates, carbon intensity, and carbon footprint of urban activities;
- *Renewable energy production*, covering the percentage of electrical and thermal demands met by renewable systems, the integration of renewable energy relative to total area consumption, and renewable production per square meter;
- *Final energy consumption*, including energy usage across residential, commercial, and industrial sectors within or attributed to the district;
- *Energy intensity*, relating energy consumption to economic activity and expressed as the ratio of final consumption to GDP;
- *Energy autonomy*, examining physical or virtual energy exchanges among buildings and emphasizing the social impact of energy self-sufficiency and distribution;
- *Transport-related emissions*, deriving from transport demand and fuel emission rates;
- *Municipal waste and recycling*, quantified by tons of recovered waste and the recycling rate for sustainable purposes.
- *Health*, considers human health impacts and toxicity;
- *Water, land use, and soil exploitation*, addressing biodiversity, land coverage for transport lines, and energy infrastructure.

As highlighted by (Walker et al., 2018), these KPIs, inspired by energy and emissions-based approaches, extend to encompass natural resource exploitation and/or conservation (Marotta et al., 2021; Xia et al., 2021). The categorization of KPIs as emissions-, energy-, and resource-based indicators, as shown in Fig. 4, underscores their interconnectedness and application across the identified macro-areas.

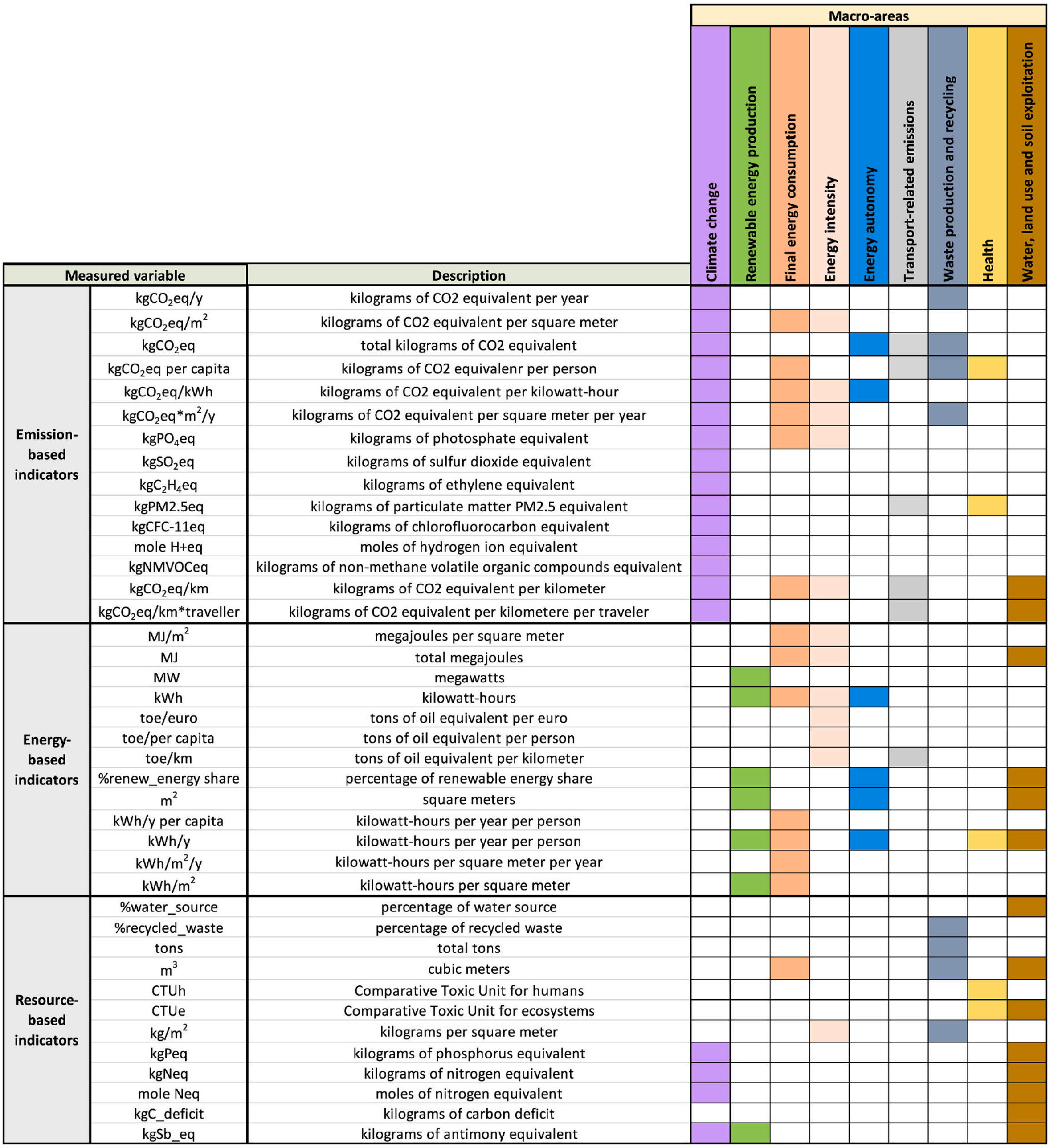
Table 4
District certification schemes.

Name	Country	Institution	No. of Items/ Criteria	No. of environmental Items/Criteria	References
LEED (ND)	USA	United States Green Building Council	56	49	U. S. G. B. Council (2009)
DGNB	Germany	German Sustainable Building Council	30	8	German Sustainable Building Council; Alexander Rudolphi et al. (2017)
CASBEE (urban development)	Japan	JSBC (Japan Sustainable Building Consortium), Institute for Building Environment and Energy Conservation (IBEC)	33	12	Murakami et al. (2007)
BREEAM (communities)	United Kingdom	BRE Global Ltd	41	12	Communities (2012)
Green Star (communities)	Australia	Green Building Council of Australia	33	9	Gelder et al. (2018)
STAR (community rating system)	USAs	Star Communities non-profit organization	49	13	Ghosh (2018)
Envirodevelopment	Australia	Urban development institute of Australia (Queensland)	117	38	Urban development institute of Australia (Queensland)
BCA (Green Mark for District)	Singapore	Building and Construction Authority	38	18	Mark (2013)
IGBC Green Townships	India	Indian Green Building Council	40	20	Council (2010)
QSAS/GSAS	Qatar	Gulf Organization for Research and Development	39	–	Tam et al. (2018)
Pearl Community rating system	United Arab of Emirates	Abu Dhabi Urban Planning Council	64	38	Abu Dhabi Urban Planning Council (2010)
Neighborhood Sustainability Framework	New Zealand	Beacon Pathway	23	–	Tam et al. (2018)
EcoDistricts (Performance and Assessment Toolkit)	USA	Portland Sustainability Institute	95	–	Tam et al. (2018)
HQE2R	Europe	European Commission (France)	51	34	Charlot-Valdieu and Outtrequin (2003)
Green Building Index Township	Malaysia	Green Building Index	45	19	Siew (2017)
Ecocity	Europe	European Commission	20	6	Huismans and Skala (2005); Gaffron et al. (2008)

Emissions-based KPIs frequently measure CO_{2eq}, reflecting the GWP, and are associated with various aspect of energy consumption (Cerón-Palma et al., 2013; Roux et al., 2016), energy intensity (Lausselet et al., 2019), and specific impacts like heating, domestic hot water, and electricity (Riera Pérez and Rey, 2013), or normalizing it with the total surface of the heated area in buildings (Lausselet et al., 2020a). KPIs concerning water, soil, and land exploitation specifically address acidification and eutrophication effects, often expressed in terms of SO_{2eq}, NO_x, or phosphates: the impact of acidification at the urban level can be derived for inhabitants, dwelling, and per square meters (Nematchoua et al., 2020; Nematchoua and Reiter, 2019). Significant studies have developed specialized KPIs aimed at assessing ozone depletion and biodiversity loss attributable to urban areas. These KPIs expand to include the assessment of photochemical oxidation potential, quantified in terms of kilograms of ethylene-equivalent (Guarino et al., 2020; Nematchoua et al., 2019; Nematchoua and Reiter, 2019). KPIs focusing on the environmental performance of buildings and districts frequently correlate with mobility measures, calculated per kilometre or per traveller (Lausselet et al., 2019, 2020a; Nematchoua et al., 2020; Moroke et al., 2019), and extend to sectors directly related to urban necessities, such as food logistics (Cerón-Palma et al., 2013) and waste management (Paiho et al., 2021). In some instances, emissions-based KPIs are applied more specifically to assess health impacts (Guarino et al., 2020; Nematchoua et al., 2019, 2020), inform economic strategies for renovation (Nematchoua et al., 2019), forecast the implications of carbon taxation (Roux et al., 2016), or enhance social awareness regarding emissions from energy use or transportation (Walker et al., 2018; Riera Pérez and Rey, 2013). The second category encompasses energy-based indicators, predominantly evaluating the energy performance of districts through the lens of inhabitant energy consumption and the integration of renewable energy sources within or adjacent to buildings.

These KPIs, often annualized, are typically expressed in kilowatt-hours (kWh) or megawatt-hours (MWh), and less frequently in tonnes of oil equivalent (toe), especially when relating to economic activities (toe/euro or toe/capita) or mobility (toe/km) (Neves and Leal, 2010). The incorporation of renewable energy is crucial in assessing district energy performance, considering aspects like energy savings potential (Hachem-Vermette and Grewal, 2019), installation area in square meters (Bambara et al., 2021), renewable energy production across various timeframes, and the proportion of renewable energy utilized (Neves and Leal, 2010). The impact of renewable energy penetration at the district level notably includes enhancing consumer roles in the energy supply chain, particularly through increase self-sufficiency and active participation in distribution processes (Fichera et al., 2020a). Energy autonomy is linked to overall production (Hachem-Vermette and Grewal, 2019; Bambara et al., 2021), the extent of rooftop coverage (Lausselet et al., 2019), and the proportion of self-consumed energy (Fichera et al., 2020b). Furthermore, KPI formulations also intersect with mobility (Mastrucci et al., 2017; Ghosh, 2018), health impact assessment (Lausselet et al., 2020b), waste-to-energy initiatives (Lausselet et al., 2019), and the development of energy infrastructures facilitating energy distribution among prosumers (Fichera et al., 2020b). Lastly, resource-based indicators primarily assess the depletion of minerals, soil, and general resources (Guarino et al., 2020; Nematchoua et al., 2020; Walker et al., 2018; Roux et al., 2016), typically quantified in cubic meters or tons. These indicators are largely associated with waste generation, water usage, and the exploitation of land and soil. KPIs also extend to sectors like food production (Paiho et al., 2021), transportation (Nematchoua et al., 2020), health impacts (Nematchoua et al., 2019; Nematchoua and Reiter, 2019), and the categorization of human toxicity effects – distinguished between cancerous and non-cancerous impacts, CTUh (Guarino et al., 2020). They cover biodiversity concerns (Nematchoua et al., 2020) and address eutrophication in freshwater, marine, and terrestrial ecosystems (Guarino et al., 2020).

The selection of specific KPIs for evaluating the performance of PEDs and, more broadly, at the city or district level, deserves further exploration considering the stakeholders involved, the application of KPI outputs, and the engagement of various actors in the adoption process.



			Macro-areas								
Measured variable		Description	Climate change	Renewable energy production	Final energy consumption	Energy intensity	Energy autonomy	Transport-related emissions	Waste production and recycling	Health	Water, land use and soil exploitation
Emission-based indicators	$kgCO_2eq/y$	kilograms of CO2 equivalent per year	■						■		
	$kgCO_2eq/m^2$	kilograms of CO2 equivalent per square meter	■		■	■					
	$kgCO_2eq$	total kilograms of CO2 equivalent	■				■	■	■		
	$kgCO_2eq$ per capita	kilograms of CO2 equivalenr per person	■		■			■	■	■	
	$kgCO_2eq/kWh$	kilograms of CO2 equivalent per kilowatt-hour	■		■	■	■				
	$kgCO_2eq*m^2/y$	kilograms of CO2 equivalent per square meter per year	■		■	■			■		
	$kgPO_4eq$	kilograms of photosphate equivalent	■		■	■					
	$kgSO_2eq$	kilograms of sulfur dioxide equivalent	■								
	kgC_2H_4eq	kilograms of ethylene equivalent	■								
	kgPM2.5eq	kilograms of particulate matter PM2.5 equivalent	■					■		■	
	kgCFC-11eq	kilograms of chlorofluorocarbon equivalent	■								
	mole H+eq	moles of hydrogen ion equivalent	■								
	kgNMVOCeq	kilograms of non-methane volatile organic compounds equivalent	■								
	$kgCO_2eq/km$	kilograms of CO2 equivalent per kilometer	■		■	■		■			■
	$kgCO_2eq/km*traveller$	kilograms of CO2 equivalent per kilometere per traveler	■					■			■
Energy-based indicators	MJ/m^2	megajoules per square meter			■	■					
	MJ	total megajoules			■	■					■
	MW	megawatts		■							
	kWh	kilowatt-hours		■	■	■	■				
	toe/euro	tons of oil equivalent per euro				■					
	toe/per capita	tons of oil equivalent per person				■					
	toe/km	tons of oil equivalent per kilometer				■		■			
	%renew_energy share	percentage of renewable energy share		■			■				■
	m^2	square meters		■			■				■
	kWh/y per capita	kilowatt-hours per year per person			■						
	kWh/y	kilowatt-hours per year per person		■	■		■			■	■
	$kWh/m^2/y$	kilowatt-hours per square meter per year			■						
	kWh/m^2	kilowatt-hours per square meter		■	■						
Resource-based indicators	%water_source	percentage of water source									■
	%recycled_waste	percentage of recycled waste							■		
	tons	total tons							■		
	m^3	cubic meters			■				■		■
	CTUh	Comparative Toxic Unit for humans								■	
	CTUe	Comparative Toxic Unit for ecosystems								■	■
	kg/m^2	kilograms per square meter				■			■		
	kgPeq	kilograms of phosphorus equivalent	■								■
	kgNeq	kilograms of nitrogen equivalent	■								■
	mole Neq	moles of nitrogen equivalent	■								■
	kgC_deficit	kilograms of carbon deficit									■
	kgSb_eq	kilograms of antimony equivalent	■	■							■

Fig. 4. Some insights on the correlation between macro-areas and measured emissions-, energy-, and resource-based KPIs.

Particularly in the context of designing new PEDs, KPIs play a crucial role in guiding the planning and decision-making stages. For existing pilot areas, KPIs offer valuable insights for assessing replication opportunities, investment potential, and the energy and environmental impacts of implemented decision. Importantly, the concept of PEDs extends beyond new constructions to encompass existing urban conglomerates, which represent a larger share of habitable spaces. In this regard, KPIs are instrumental in assessing the effectiveness of renewable energy integration and the impacts of various technological configurations, such as energy storage and management systems including curtailments, demand response, and trading schemes. KPIs are also vital for policymakers in assessing the effectiveness of subsidies and regulations, thereby facilitating the successful implementation of PEDs. The methodology for performance evaluation and monitoring of KPIs encompasses diverse approaches, as illustrated in the Sankey chart of Fig. 5, where the thickness of the connections indicates the prevalence of contributions in that area. These connections were quantified based on a comprehensive literature review and data analysis of the frequency and impact of each approaches on the respective macro areas. LCA emerges as the leading method, reflecting its extensive application in assessing the environmental impacts of processes and technologies. This is evidenced by numerous studies focusing on KPIs related to 'climate change' (Guarino et al., 2020; Lausselet et al., 2020a; Riera Pérez and Rey, 2013; Roux et al., 2016) and 'water, land use, and soil exploitation' (Guarino et al., 2020; Nematchoua et al., 2020). These studies quantify contributions by analysing the number of publications, case studies, and the depth of environmental impact assessments conducted using LCA. Attention is also given to 'waste production and recycling' to understand the lifecycle from extraction or processing to disposal. Optimization models and case study simulations follow as prominent approaches, predominantly used to evaluate the performance of various energy technologies (Braimakis et al., 2021; Pursiheimo and Rämä, 2021; Weiss et al., 2021; Tonellato et al., 2021). The quantification here involves analysing how these models are employed to enhance energy efficiency,

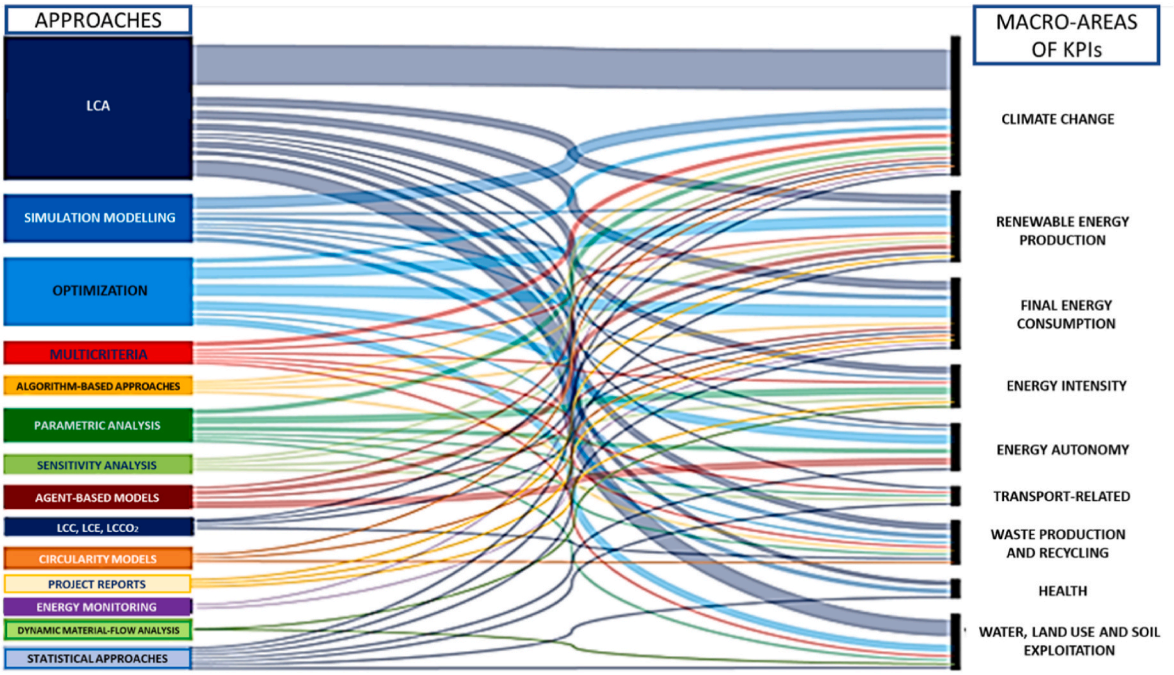


Fig. 5. Most commonly employed methodological approaches.

optimize resource use, and improve technology integration to fulfill energy consumption needs, enhance consumer self-sufficiency, and facilitate energy distribution within districts (Fichera et al., 2020a). The development of KPIs focused on environmental performance often centers on estimating carbon dioxide savings compared to fossil fuel use and conventional mobility options (Paiho et al., 2021). The frequency and detailed application of these models in specific studies provided the basis for their connection thickness in the Sankey chart. Energy aspects, particularly renewable production or consumption (Guarino et al., 2020; Walker et al., 2018; Nematchoua et al., 2019) and energy intensity (Lausselet et al., 2019, 2020b), receive uniform coverage, though 'energy autonomy' for end-users and 'transport-related' issues are less emphasized. This uniformity is quantified by the consistency and spread of research focusing on these areas, ensuring a balanced representation in the chart. Beyond these approaches, performance indicators are crafted to interpret results from diverse and heterogeneous analyses. Heuristic and semi-heuristic formulations, agent-based models, and genetic algorithms are typically employed to assess consumer energy autonomy (Fichera et al., 2020b) or to explore energy valorization at the district level (Hachem-Vermette and Grewal, 2019). Statistical and sensitivity analyses, frequently paired with optimization models or LCA (Janssens et al., 2017; Lausselet et al., 2019), provide a comprehensive framework for assessing and enhancing PED performance and sustainability.

Apart from the scientific literature, definitions and usability of KPIs derive also from the International Standards, that provide a common framework for standardized measures, data source utilization and benchmarking for the performance evaluation of urban areas. The ISO 37120:2018 on "Sustainable development of communities – Indicators for city services and quality of life" was released in 2014 and has been updated in 2018 (I. O. for Standardization, 2014). It covers an extensive set of urban spheres linked to city services and to the quality of life in urban settlements. Some of the most relevant for the environmental impact assessment can be recognized in: environment and climate change, energy, housing, population and social conditions, solid waste, health, urban planning, transportation, and so on. The Standard recognizes three typologies of KPIs, i.e., "core indicators", considered fundamental to evaluate the performances of cities; "supporting indicators", recommended yet voluntary performance measures, and "profile indicators", mostly use to inform stakeholders. The formulation of supplementary KPIs has been made available in the ISO 37122:2019 on "Sustainable cities and communities – Indicators for smart cities" (I. O. for Standardization, 2019) and in the ISO 37123:2020 on "Sustainable cities and communities – Indicators for resilient cities" (Work et al., 2015). The majority of these KPIs are expressed in terms of percentages, such as the percentage of electrical energy produced from decentralized energy systems, the percentage of refurbished buildings, the percentage of buildings with smart energy or water meters, the percentage of energy generated from waste, the percentage of low-emissions vehicles, to quote a few.

As a further remark, a large set of indicators derives from the Sustainable Development Goals framework of the United Nations established within the 2030 Agenda for Sustainable Development (Work et al., 2015). In this direction, particular attention should be devoted to SDG7 "Affordable and Clean Energy", SDG11 "Sustainable Cities and Communities", SDG 12 "Responsible production and consumption" and SDG13 "Climate Action". The linkage between SDGs and PEDs has to be considered strategical for the achievement of the energetic, environmental, economic, and social sustainability of urban areas (Cellura et al., 2022). As highlighted in this research, SDGs targets and related indicators can be shaped around the performance evaluation needs of PEDs to give insights on how the positive surplus of these districts can contribute to targeting the UNs' indications.

5. Results analysis

This section presents a comparison of the results from different LCA analyses applied to various districts. However, given the discrepancies among the studies, such as functional units, system boundaries, or assumptions made for each life cycle stage, the primary aim of this comparison is to gauge the environmental impact magnitudes generated throughout the lifecycle of the case studies reviewed in the literature. Additionally, several factors influencing each stage of the district lifecycle should be considered. For instance, uncertainties affecting the use stage energy consumption include climate, occupants' behavior, district shape, and the country's electricity generation mix; meanwhile, the impacts during the pre-use stage are influenced by the construction material used or the distances involved in material transportation. The literature review identified 15 researches accounting for 22 district case studies. The key analysis points of the reviewed papers are summarized in Table 3. Specifically, 68% of the selected case studies are situated in Europe, with 4 case studies in the USA, 2 in Canada, and 1 in Australia. Among the 22 case studies examined, 9 are residential districts, while 11 feature mixed uses.

Due to the diversity of case studies and the variety of functional units employed in the reviewed papers, summarizing results in a format that allows for comparison between case studies is challenging. Where available, results for four different functional units were calculated: the entire district, per district occupant, per square meter of district, and per square meter of heated floor area (HFA) of the district.

The case studies have been analysed into unified tables to facilitate direct comparison. For the GWP, all data are presented in Table 5 and for the GER, all data are in Table 6.

In these tables, concise abbreviations are used to enhance clarity and readability. The building types are indicated as ‘R’ for Residential and ‘Mix’ for Mixed Uses. The system boundaries are denoted by ‘B’ (Building), ‘M’ (Mobility), ‘ES’ (Energy System), and ‘OS’ (Open Space). The life cycle stages considered in each case study are represented by ‘Cons.’ (Construction), ‘Oper.’ (Operation), ‘Main.’ (Maintenance), and ‘Decon.’ (Deconstruction).

For instance, a case study that includes construction and operation stages is noted as ‘Cons./Oper.’, while one encompassing construction, operation, and maintenance is indicated as ‘Cons./Oper./Main.’.

These abbreviations are consistently applied within Tables 5 and 6 to streamline the presentation and facilitate easier comparison across the different case studies.

Only these two environmental impact categories were comparable across almost all the reviewed studies. The analysis of the reviewed case studies shows that GHG emissions range from 105.3 ton CO$_{2eq}$/year (Lausselet et al., 2020a) to 5430 ton CO$_{2eq}$/year (Stephan et al., 2013), while primary energy consumption varies from 5 TJ/year (Peuportier and Roux, 2013; Herfray, 2011) to 559.5 TJ/year (Nichols and Kockelman, 2014). This variability covers two orders of magnitude for GWP and primary energy consumption on a district basis.

When examining environmental impacts per district inhabitant, GHG emissions span from 1090 kg CO$_{2eq}$/(inhabitant per year) to 17,322 kg CO$_{2eq}$/(inhabitant per year), and primary energy consumption ranges from 6 GJ/(inhabitant per year) to 115 GJ/(inhabitant per year).

Moreover, regarding environmental impacts per square meter of district, GWP values lies between 3.6 kg CO$_{2eq}$/(m^2 per year) and 295 kg CO$_{2eq}$/(m^2 per year), while GER values range from 48 MJ/(m^2 per year) to 5600 MJ (m^2 per year).

Considering the impacts per square meter of HFA, GWP varies from 11 kg CO$_{2eq}$/(m^2 per year) to 107 CO$_{2eq}$/(m^2 per year), and GER from 74 MJ/(m^2 per year) to 1665 MJ/(m^2 per year). From the studies outlined in Table 5, 9 case studies from seven papers (Lausselet et al., 2020a, 2021; Stephan et al., 2013; Norman et al., 2006; Colombert et al., 2011; Herfray, 2011; Peuportier et al., 2006) are comparable due identical system boundaries regarding life cycle steps, specifically Buildings, Mobility, and Energy Systems. Among these studies, GWP ranges from 1100 kg CO$_{2eq}$/(inhabitant per year) to 8637 kg CO$_{2eq}$/(inhabitant per year). Specifically focusing on mixed communities, 10 case studies from 7 papers (Nematchoua et al., 2019, 2020; Lotteau et al., 2015a; Lausselet et al., 2019, 2021; Riera Pérez and Rey, 2013; Colombert et al., 2011; Herfray, 2011; Peuportier et al., 2006) are comparable, with GWP ranging from 315 ton CO$_{2eq}$/year to 4586 ton CO$_{2eq}$/year, averaging about 1652 ton CO$_{2eq}$/year. On the other hand, analysing the gross energy requirement (GER) detailed in Table 6, seven case studies from three papers (Peuportier and Roux, 2013; Norman et al., 2006; Herfray, 2011) show a GER range from 5.7 GJ/(inhabitant per year) to 86 GJ/(inhabitant per year). This range was determined by applying specific filtering criteria based on consistent boundary conditions (B, M, ES) and life cycle stages (Cons, Oper, Decom). Focusing on mixed communities, seven case studies (Hachem-Vermette and Grewal, 2019; Peuportier and Roux, 2013; Riera Pérez and Rey, 2013; Colombert et al., 2011; Herfray, 2011; Peuportier et al., 2006) are comparable, with GER ranging from 5 TJ/year to 103 TJ/year and an average value of about 31 TJ/year.

Additionally, a minor portion of the studies (Lotteau et al., 2015a; Lausselet et al., 2019, 2021; Stephan et al., 2013) reported in Table 5 allowed for an analysis of the contributions to the environmental impacts, specifically GWP, by different district elements divided into buildings, mobility, open spaces/infrastructures, and energy systems. As indicated in Table 7, all studies identify buildings as the major contributors to GHG emissions, with their impact percentage ranging from 22% (Stephan et al., 2013) to 50% (Lotteau et al., 2015a), followed by

Table 5

District LCA results: Global warming potential (GWP), (B is abbreviation for Buildings, M is abbreviation for Mobility, ES is abbreviation for Energy Systems, OS is abbreviation for Open Space, Cons. is abbreviation for Construction, Oper. is abbreviation for Operation, Main. is abbreviation for maintenance, Decon. is abbreviation for Deconstruction).

Country	Type	Boundaries	LC stages	ton CO$_{2eq}$/ year	kg CO$_{2eq}$/ (inhabitant*year)	kg CO$_{2eq}$/ (m^{2}year)	kg CO$_{2eq}$/(m^2 (HFA)*year)	Ref.
Norway	R	B, M and ES	Cons., Oper.	105.3	1320.0	–	32.9	Lausselet et al. (2020a)
France	Mix	B, OS and M	Cons, Oper	315.6	1100.0	–	–	Lotteau et al. (2015a)
Australia	R	B, M and ES	Cons., Oper.	5430.0	7255.0	3.6	–	Stephan et al. (2013)
Norway	Mix	B, OS, M and ES	Cons., Oper., Main.	1950.0	1500.0	21.2	–	Lausselet et al. (2019)
Canada	R (2 case study)	B, M and ES	Cons, Oper., Decon.	– –	8637.0 3341.0	– –	107.3 77.7	Norman et al. (2006)
Switzerland	Mix	B and M	Cons., Oper., Decon.	4586.4	4457.1	65.5	78.0	Riera Pérez and Rey (2013)
France	Mix	B, M and ES	Cons., Oper., Decon.	2301.5	–	15.3	26.1	Colombert et al. (2011)
Germany	Mix (2 case study)	B, M and ES	Cons., Oper., Decon.	400.0 500.0	1100.0 1200.0	17.6 12.5	– –	Herfray (2011)
France	R	B	Cons., Oper., Decon.	1930.0	–	–	–	Cherqui (2005)
France	Mix	B, M and ES	Cons., Oper., Decon.	800.0	–	–	10.8	Peuportier et al. (2006)
Belgium	Mix (2 case study)	B	Cons., Oper., Main., Decon.	– –	5084.0 17322.0	295.2 294.1	– –	Nematchoua et al. (2019), (2020)
Norway	Mix	B, M,OS and ES	Cons., Oper., Main., Decon.	2366.7	–	–	–	Lausselet et al. (2021)

Table 6
District LCA results: gross energy requirement (GER). (B is abbreviation for Buildings, M is abbreviation for Mobility, ES is abbreviation for Energy Systems, OS is abbreviation for Open Space, Cons. is abbreviation for Construction, Oper. is abbreviation for Operation, Main. is abbreviation for maintenance, Decon. is abbreviation for Deconstruction).

Country	Type	Boundaries	LC stages	TJ/year	GJ/(Inhabitant*year)	MJ/(m^2year)	MJ/(m^2 (HFA)* year)	Ref.
USA	R. (4 case studies)	B.,M.,ES	Cons., Oper.	559.5	115.0	110.6	–	Nichols and Kockelman (2014)
			Cons., Oper.	376.8	111.0	589.0	–	
			Cons., Oper.	479.1	97.0	557.1	–	
			Cons., Oper.	556.4	72.0	1112.8	–	
France	Mix	B, OS and M	Cons., Oper.	7.0	24.3	0.0	–	Lotteau et al. (2015a)
Australia	R	B., M., ES	Cons., Oper.	73.0	97.5	48.7	1664.8	Stephan et al. (2013)
Canada	R (2 case studies)	B, M and ES	Cons., Oper., Decon.	–	86.0	–	1068.0	Norman et al. (2006)
				–	40.1	–	936.0	
Switzerland	Mix	B, M	Cons., Oper., Decon.	79.5	77.3	1135.7	1352.0	Riera Pérez and Rey (2013)
France	Mix	B, M and ES	Cons., Oper., Decon.	103.4	–	689.1	1172.4	Colombert et al. (2011)
Germany	Mix (2 case studies)	B, M and ES	Cons., Oper., Decon.	5.7	14.4	236.8	–	Herfray (2011)
				8.6	13.2	427.5	438.5	
France	Mix	B, M and ES	Cons., Oper., Decon.	15.1	17.0	158.0	281.3	Peuportier and Roux (2013);
Germany	Mix (2 case studies)	B, M and ES	Cons., Oper., Decon.	18.6	21.0	550.8	346.9	Herfray (2011)
				5.0	5.7	140.1	74.0	
France	R	B	Cons., Oper., Decon.	47.6	–	–	0.0	Cherqui (2005)
France	Mix	B, M and ES	Cons., Oper., Decon.	63.0	–	–	840.0	Peuportier et al. (2006)
Belgium	Mix (4 case studies)	B	Cons., Oper., Main., Decon.	–	96.7	5600.0	–	Nematchoua et al. (2019), (2020)
				–	27.6	4700.0	–	

Table 7
District LCA results: Global warming potential (GWP).

Buildings	Mobility	Open spaces/ infrastructures	On-site energy	References
52%	40%	3%	5%	Lausselet et al. (2019)
50%	45%	5%	Not analysed	Lotteau et al. (2015a)
35%	35%	13%	17%	Lausselet et al. (2021)
22%	36%	Not analysed	42%	Stephan et al. (2013)

mobility, with an environmental impact contribution ranging from is between 35% (Lausselet et al., 2021) to 45% (Lotteau et al., 2015a), while open spaces and energy systems have limited impacts.

To conclude, the analysis of the reviewed case studies is visually summarized in Fig. 6 for GWP and in Fig. 7 for GER. In each boxplot, the median value is represented by the segment inside the box, with the edges of the box indicating the 25th and 75th percentiles, and the whiskers extending to the extreme values. For the results corresponding to the entire district, GWP exhibit a median value of approximately 1930 ton CO_{2eq}/year, with the 25th and 75th percentiles at 450 ton CO_{2eq}/year and 2334 ton CO_{2eq}/year, respectively. Similarly, GER shows a median value of around 63 TJ/year, with the 25th and 75th percentiles at 12 TJ/year and 240 TJ/year, respectively. When analysing the environmental impacts per district inhabitant, GHG emissions present a median value of about 3341 kg CO_{2eq}/(inhabitant per year), with the 25th and 75th percentiles at 1260 kg CO_{2eq}/(inhabitant per year) and 6169 kg CO2eq/(inhabitant per year), respectively. Primary energy consumption has a median value of approximately 56 GJ/(inhabitant per year), with the 25th and 75th percentiles at 20 GJ/(inhabitant per year) and 94 GJ/(inhabitant per year), respectively. Considering the environmental impacts per square meter of district, the GWP median value is 19 kg CO_{2eq}/(m^2year), while the GER median values is 332 MJ/(m^2year). Lastly, evaluating the environmental impacts per square meter of HFA, the GWP median value is 55.3 kg CO_{2eq}/(m^2year), and the GER median values is equal to 888 MJ/(m^2year).

The analysis of GER and GWP data across 22 district case studies underscores the complexity and significant variability, with GHG emissions ranging from 105.3 ton CO_{2eq}/year to 5430 ton CO_{2eq}/year and primary energy consumption spanning from 5 TJ/year to 559.5 TJ/

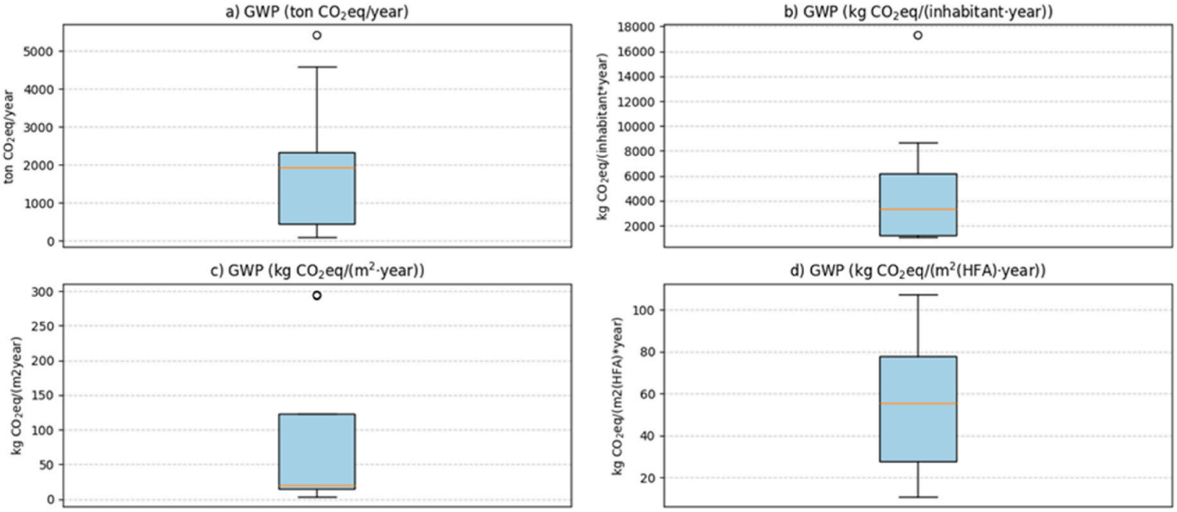


Fig. 6. GWP: min, Q1, median, Q3 for different FUs.

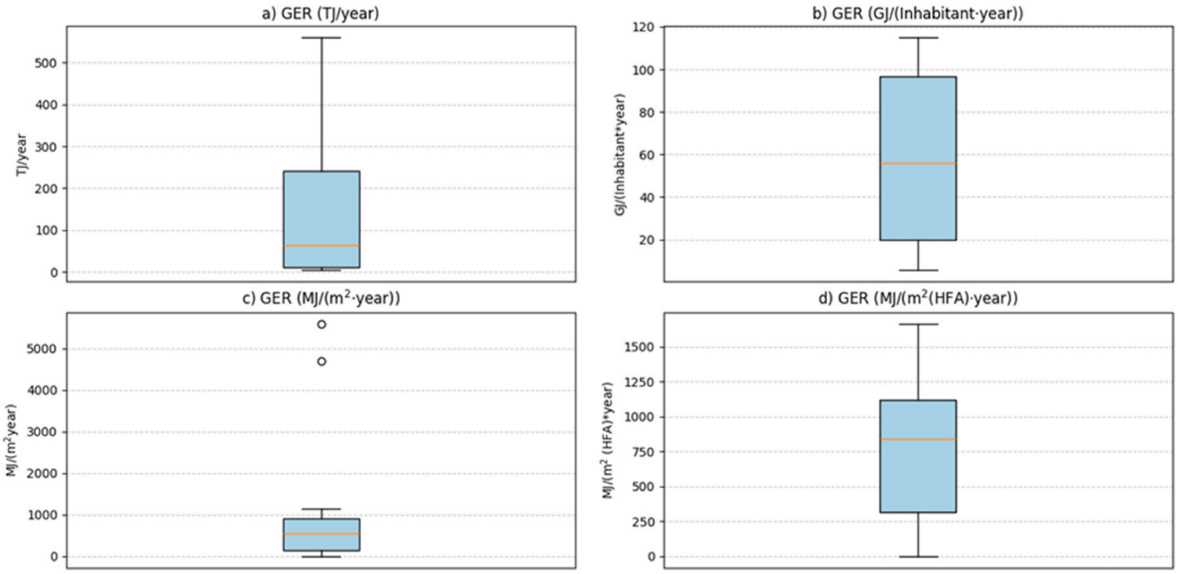


Fig. 7. GER: min, Q1, median and Q3 for different FUs.

year. The wide range of values, influenced by varying system boundaries, lifecycle stages and metrics, highlights the necessity for flexible and context-specific eco-design strategies. This variability suggests that eco-oriented design must be adaptable, considering the unique characteristics and operational contexts of each district to effectively reduce energy consumption and emissions. In this regard, the Energy Performance of Buildings Directive (EPBD) and the Zero Emission Building concept present an opportunity to propose uniform, building-related calculation standards and streamline the assessment of embodied environmental impacts. By adopting coherent criteria and harmonized procedures, it becomes possible to simplify comparisons and ensure greater transparency. Such an approach facilitates a more straightforward progression toward buildings with reduced environmental footprints and clearly defined performance targets at the district level."

6. Research gaps and concluding remarks

The approach to assessing the environmental sustainability of PEDs varies significantly in terms of system boundaries and environmental KPIs adopted as metrics. The methodologies employed differ in depth according to the study's objectives and scope: they range from a basic use stage perspective, typically focused on modelling/monitoring energy use and emission analysis, to a more comprehensive Life Cycle Assessment (LCA) approach.

Regarding the main KPIs used, a significant portion is inspired by energy-based or emissions-based approaches. In addition to energy and environmental themes, some studies emphasize the importance of setting performance measurements in terms of the exploitation and/or conservation of natural resources. Nonetheless, the quantitative assessment of most KPIs mentioned is often not directly comparable due to diverse system boundaries and methodological assumptions employed in the literature. For instance, taking the impact category of global warming potential (GWP) as an example, the quantitative metric evaluated varies, sometimes corresponding to the district's area, other times to the walkable area of the built environment, and is sometimes annualized or simply reported as aggregate emissions. The system boundaries also vary, distinguishing between facilities and aspects of the district (e.g., onsite energy supply systems, buildings, mobility, impacts allocation), as well as the life cycle stages included.

Therefore, the state-of-the-art analysis for the environmental impact assessment of PEDs highlights several research gaps and opportunities.

- There is a pressing need for a standardized approach to assessing environmental impacts at district scale, employing diverse scopes and indicators. Given that the chosen assessment methods significantly influence the results and their validity, transparent approaches are essential to prevent misleading outcomes that could lead to inaccurate decision-making.
- The practice of merely mentioning and calculating KPIs without exploring the trade-offs between design alternatives is prevalent. There is a call for integrated and systematic analyses to better address this aspect, promoting a more comprehensive understanding of the impacts of different design choices.
- The environmental impacts of a district go beyond the use phase, encompassing embodied energy and environmental burdens from resource extraction, manufacturing, construction activities, and the disposal of construction waste at the end of life. Since life cycle impacts are highly interdependent, with one phase potentially influencing others, the assessment focus should extend to all life cycle stages, including the indirect emissions caused by buildings, infrastructures, and activities within the district. This holistic perspective is increasingly vital as the environmental impacts of low-energy buildings or Nearly Zero-Energy Building (NZEBs) shift from the use stage to other life cycle stages.
- To prevent burden shifting between environmental impacts, a holistic and integrated consideration of impacts is necessary. Thus, the range of indicators for Life Cycle Impact Assessment (LCIA) should expand beyond GWP and cumulative energy demand to include other impact categories critical for district planning, such as resource depletion and air-pollution related impacts along the material supply chain.
- Additional research in the field of LCA at the district level is crucial, focusing on the significant life cycle stages and physical elements contributing to various environmental impact categories and understanding the critical factors influencing emissions and impact results in different contexts. The variation in system boundaries, temporal horizons, building life cycle stages considered, and functional units among studies complicates the comparison of results, highlighting the need for transparent and flexibly disaggregated LCA results at the district level. Moreover, employing LCA as a tool in the early planning stages of new district projects can fully leverage its potential.
- Uncertainty and sensitivity analyses are seldom conducted by are highly recommended to address the significant effects of missing

information and assumptions on large building stocks. Few studies have quantitatively approached this issue, emphasizing the need for results validation and the development of surrogate models for a reliable prediction of building energy consumption.

- Most current studies do not account for long-term technological developments and improvements in production processes for replacement materials. Investigating more dynamic approaches and systematic, transparent integration with other modelling scenarios, such as energy scenarios through dynamic LCA, is necessary.
- There is potential to include spatial constraints and identify hotspots, where GIS integration can enhance spatial information management and model accuracy. Integrating GIS with districts energy analysis and LCA could offer a series of advantages. The use of spatially-explicit data contributes to the refinement and enrichment of the building inventory, making it possible to explicitly consider spatial constraints, e.g. linked to resource supply, site-specific characteristics, current and future infrastructures and networks, suitability of renewable energy installations. Finally, GIS can be used to display results as spatial maps for improved communication.
- The connection between PED assessment results and higher-level environmental targets, such as city and national climate goals and sustainable development goals, is currently lacking and needs strengthening.

CRediT authorship contribution statement

Rosaria Volpe: Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Adriano Bisello:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Andreas Tuerk:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Francesco Guarino:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Emanuela Giancola:** Writing – original draft, Investigation. **Maria Nuria Sanchez:** Writing – original draft, Investigation. **Giovanni Tumminia:** Writing – original draft, Investigation. **Elisa Marrasso:** Writing – original draft, Investigation. **Giovanna Pallotta:** Writing – original draft, Investigation. **Emanuele Cutore:** Writing – review & editing, Writing – original draft, Investigation. **Maurizio Cellura:** Investigation. **Alberto Fichera:** Investigation. **Sonia Longo:** Investigation. **Carlo Roselli:** Investigation. **Maurizio Sasso:** Investigation. **Xiaojin Zhang:** Writing – review & editing, Investigation. **Ilaria Marotta:** Writing – review & editing, Writing – original draft, Investigation. **Alberto Brunetti:** Writing – review & editing, Investigation. **Roberta Rincione:** Writing – review & editing, Investigation. **Francesco Reda:** Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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