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Life Cycle Assessment as a Tool for Advancing Positive Energy Districts: A Systematic Literature Review

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Abstract **– Cities and their inhabitants are among the largest consumers of energy and contributors to environmental pollution, accounting for 70 % of global greenhouse gas emissions. One of the European Union's key strategies for addressing this issue is the development of Positive Energy Districts (PEDs). Although some PEDs already exist, the concept remains an emerging field of study that goes beyond achieving neighborhoods with net-zero energy imports – or even net-positive energy production. It also emphasizes sustainability and the reduction of greenhouse gas (GHG) emissions. This article explores solutions for implementing PEDs, focusing on energy flow analysis and Life Cycle Assessment (LCA) to inform decision-making. Developing PEDs is a multifaceted process that involves improving building energy efficiency, assessing existing energy sources, exploring opportunities for on-site energy generation, integrating renewable energy systems, and ensuring efficient storage of generated energy. A significant aspect of LCA is calculating embodied emissions for all PED-related implementations, particularly in existing districts where substantial improvements are needed to meet PED goals. In such cases, LCA plays a crucial role in ensuring not only net-zero energy imports but also meaningful GHG emission reduction. Although LCA is not yet widely applied in the development of PEDs, this article highlights its importance in addressing key aspects of achieving climate neutrality goals, when transforming urban areas to PEDs.**

Keywords **– Buildings; climate neutrality; energy efficiency; energy flexibility; energy production; urban areas; zero emissions.**

1. INTRODUCTION

The building sector is among the largest contributors to global energy consumption and greenhouse gas emission (GHG) emissions [1].

The focus in the building sector is shifting beyond individual buildings and their energy efficiency toward a broader perspective that includes neighborhoods, building clusters, and entire cities. Research and policy initiatives increasingly recognize that expanding building-level strategies is essential for accelerating GHG reductions. This broader approach not only

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enhances energy efficiency but also enables synergies among multiple buildings, optimizing the integration of renewable energy sources and maximizing overall sustainability [2]–[4].

This shift in perspective is essential to integrating the entire building energy infrastructure into a comprehensive decarbonization effort. It accounts for the complexities of building interactions, energy flexibility, grid integration, and load matching, ensuring a more efficient and sustainable energy system [2].

Positive Energy Districts (PED) are defined as "energy-efficient and energy-flexible urban areas which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy" [5]. EU has formulated the SET-Plan ACTION No 3.2 Implementation Plan to facilitate the deployment of PEDs, which includes the development of guidelines and conditions for achieving PED status [6]. However, the methodology itself is under development [7].

Positive Energy Districts (PEDs) have emerged as a key model for driving the transition toward more sustainable, resilient, and affordable urban settlements. They are being developed as essential components of energy-efficient environments, aligning with international sustainable development goals. PEDs embody self-production, self-consumption, and zero emissions, offering a transformative approach to urban energy use while also addressing social inclusiveness, stakeholder engagement, and economic considerations. As innovative urban areas with a positive energy balance, PEDs inherently prioritize sustainability, energy efficiency, sustainable mobility, and the integration of renewable resources [3]. The implementation of PEDs is anticipated to greatly enhance the sustainability of urban energy systems [1]. The district, positioned as an intermediate urban scale between individual buildings and the city as a whole, provides a more comprehensive framework for assessing building energy performance, characteristics, and the surrounding urban context. Additionally, it facilitates the effective integration of on-site and nearby renewable energy generation and distribution systems [8].

From an environmental perspective, higher retrofitting standards lead to lower grid electricity-related carbon emissions. Additionally, retrofitted PEDs require less energy infrastructure, reducing embedded emissions and conserving raw materials. However, the production and installation of retrofitting materials also contribute to emissions [9].

One key challenge is the varying difficulty of implementing these solutions in newly built districts versus existing neighborhoods, particularly from technical and regulatory perspectives. Much of the EU's built environment predates energy efficiency legislation, making retrofitting a priority. However, this often conflicts with regulations protecting historic city centers. Additionally, a frequently overlooked issue is the comprehensive assessment of both direct and indirect carbon emissions—typically focused on the operational phase—when defining and achieving Positive Energy Districts (PEDs). This remains a topic of ongoing debate without a universally accepted framework at the international level [2].

While newly constructed houses are often designed to be sustainable, existing buildings frequently fall short of sustainability standards. Refurbishing a building instead of constructing a new one can reduce environmental impact by more than 50 %. Retrofitting or refurbishing existing buildings while simultaneously installing insulation materials and utilizing renewable energy sources (RES) is a more effective and beneficial approach to achieving short- and mid-term environmental goals than constructing new buildings with similar features [10]. This strategy enhances environmental sustainability, as the time required to offset the GHG emissions from new construction can range from 10 to 80 years – equivalent to the lifespan already surpassed by some existing buildings [11]. It is especially effective for buildings with low energy efficiency [2].

Life Cycle Assessment (LCA) is wildly used, recognized by the scientific community and an essential tool for thoroughly evaluating the environmental impacts of buildings, and evaluating embodied emissions and new operational emissions for renovation processes [10]–[12].

This review article focuses on LCA's emphasis on energy-related aspects of buildings when developing a PED.

2. Review Methodology

2.1. Bibliographic Analysis

The bibliometric method is a quantitative approach to analyzing published bibliometric data, designed to investigate the intellectual structure of a specific research field [13].

A document search was performed using the Web of Science databases, focusing on research and review articles. To capture the latest advancements, the search was limited to the past five years (2020–2025). The search employed the keywords "positive energy districts" or "positive energy district," which were applied specifically to document titles.

This data was processed using VOSviewer, an open-access tool for constructing and visualizing networks, as well as mapping relationships within various types of bibliometric data [13]. Network visualizations for co-occurrence analysis were generated, focusing on author-specified keywords. The weighting was based on the number of keyword occurrences, with a minimum threshold of five occurrences.

2.2. Systematic Literature Review

A Systematic Literature Review (SLR) is a structured research methodology used to systematically collect, identify, and critically analyze existing studies, including journal articles, conference proceedings, books, and dissertations. The primary objective is to synthesize key insights, evaluate critical aspects of existing knowledge, and identify gaps that warrant further investigation [14]. For a systematic literature review, selected documents for bibliographic analysis were used.

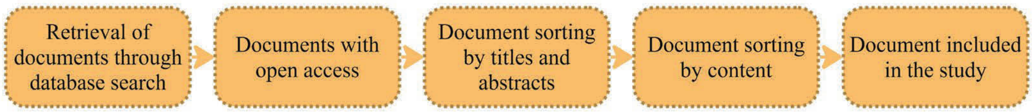

Fig. 1. Steps of Systematic Literature Review.

A total of 462 documents were retrieved through a database search, of which 313 were available as open-access publications. The selection process was conducted based on the inclusion of LCA or environmental evaluation criteria, as well as overall relevance to PEDs. Following an initial screening of titles and abstracts, 242 documents were excluded due to insufficient alignment with the research focus. There were also manually added articles.

3. Results

Bibliographic analysis shows that keywords closely linked to PEDs suggest a multidisciplinary research focus, integrating energy systems, sustainability, and urban planning – the network (Fig. 2) is structured into several interconnected clusters representing different aspects of PED research.

It is possible to see that PEDs represent a rapidly growing interdisciplinary research field, integrating aspects of energy efficiency, renewable energy, sustainability, smart cities, and governance. Their successful implementation relies heavily on technological advancements such as energy modeling, and optimization, which enhance energy performance and management. Additionally, environmental and life cycle considerations, including carbon footprint, resilience, and climate neutrality, are essential in assessing their overall impact. Beyond the technical and environmental dimensions, PEDs also involve significant social and policy aspects. Governance, economic development, and the creation of smart communities play a crucial role in establishing supportive frameworks that enable the effective scaling and long-term success of PED initiatives.

However, it is important to note that not all keywords are directly associated with PEDs. Some included documents contain related keywords, yet their content remains entirely unrelated to PEDs.

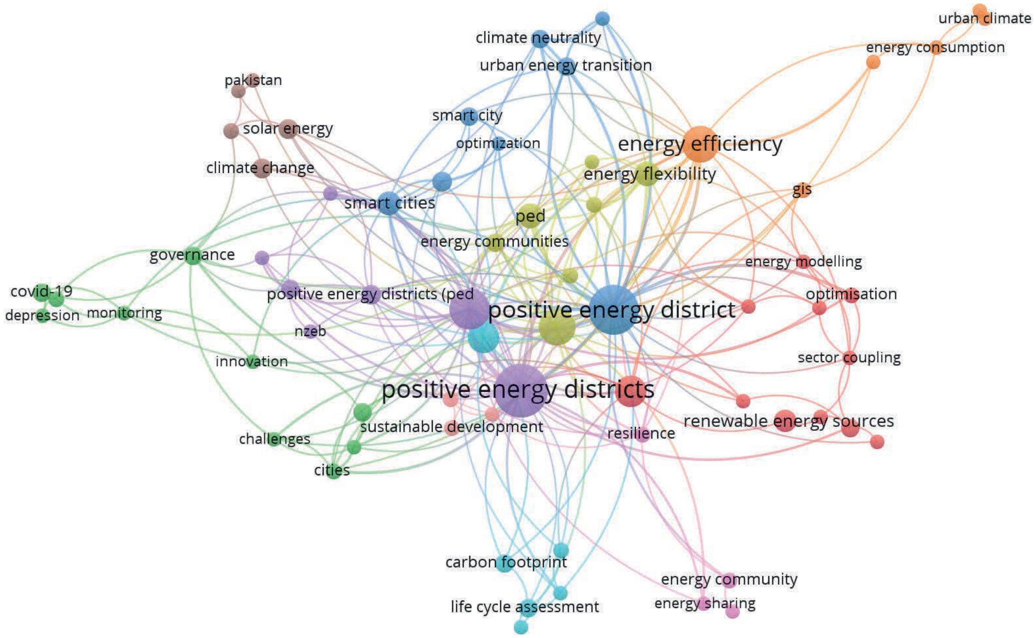

Fig. 2. Co-occurrence of author-specified keywords.

3.1. Evaluating Environmental Aspects of PED

There are studies that have included environmental evaluation (see Table 1) or have proposed a multi-criteria approach for environmental evaluation [15], Delphi-DANP approach, [8] a Baseline Emission Inventory (BEI) [1] for environmental evaluation. Vole R. [16] shows method for evaluating avoided emissions, when transitioning forward PED.

Natanian J. [17] has also summarized different PED modeling tools, that have inclusion of environmental evaluation. However, LCA is not widely used. While in some studies, LCA is used to develop PEDs, no methodology is described [2]. Without defining a functional unit, specific boundaries, and inventory, comparison is almost impossible. Thus, it cannot be used as a baseline, taking into account that for now, there is no official baseline or criteria for evaluation. Sassenou L. N. accents that further research should focus on establishing standardized norms and guidelines for GHG calculations in PEDs. This would enhance transparency, ensure consistency, minimize misunderstandings, prevent potential greenwashing, and support genuinely transformative projects [18].

TABLE 1. METHODS FOR EVALUATING ENVIRONMENTAL ASPECTS OF PEDS

Evaluation method	**Included aspects**	**Main conclusions**	**Limitations**	**Reference**
Adding GHG factor	Grid and mobility associated carbon emissions	Transition towards RER, will significantly reduce GHG emissions	No specific method described, thus not applicable	[19]
Dynamic Time-of-Use (ToU) tariff	Grid-associated carbon emissions	The higher the retrofitting standard, the lower the grid electricity-related carbon emissions.	Only grid-related CO_2 emissions are included	[9]
Weighted sum method (WSM)	Grid-associated and produced energy carbon emissions	Hydrogen is an environmentally better option than solar energy	Narrow scope and different CO_2 factors in other countries	[20]
EnergyPLAN + MOEA model	Mobility, energy consumption (grid and produced), energy storage	The use of electric storage solutions will not result in significant CO_2 emission reduction Transport sector is crucial for reducing emissions	Difficult to apply to other studies	[21]
LCA	Building operational energy use, building embodied emissions, mobility energy use	Embodied emissions for buildings should focus on renovation Inclusion of embodied emissions will unlikely to achieve net-zero emissions	Inclusion is unlikely to achieve net-zero emissions	[2]

Casamassima L. suggests that considering the focus on renewable local energy generation in PEDs, this goal of net zero emissions is likely always fulfilled [22]. However, existing studies that have incorporated environmental evaluation consistently indicate that achieving net-zero emissions remains an unattainable goal [1], [2].

3.2. Energy Efficiency of Buildings

The main energy-related aspects when developing a PED are energy efficiency of buildings, on-site energy production, and energy flexibility [9]. Unfortunately, renovation rate in most municipalities is still low [23]. Studies have demonstrated that improving the energy efficiency of buildings not only delivers substantial environmental benefits, enhances economic gains, and strengthens energy security, but also improves indoor environment quality and occupant thermal comfort [15], [24].

Building renovation will not only improve the building itself but also play a crucial role in lowering future heat consumption in cities [25] and thus lowering emissions in district heating systems. However, optimizing the energy performance of existing buildings will inevitably result in additional embodied emissions. These embodied emissions arise from the manufacturing, transportation, and replacement of materials used in renovation projects, among other processes [11]. LCA assessment for renovation includes not only stages A1–A5, which cover the product and construction phases, but also stages C1 to C4, where applicable, to ensure a comprehensive evaluation of the renovation's environmental footprint [26], [27].

As existing research indicates, LCA is widely applied in the building sector and follows a standardized methodology established within the International EPD System [34]. This structured approach ensures consistency in evaluating the environmental impact of buildings throughout their life cycle. Additionally, LCA in the context of building renovation has been extensively studied, as evidenced by the literature summarized in Table 2. The existing body of research provides a clear framework for conducting LCA in renovation projects, including well-defined guidelines for establishing the functional unit (FU), determining the expected lifetime of the building or its components, and setting appropriate system boundaries.

TABLE 2. LCA IN BUILDING RENOVATION

Authors	System boundaries	Functional unit	Lifetime	Renovation type	Impact assessment method	Impact categories	Database	Location
Serrano *et al.* [28]	A4; B4; B1; C1	"use of the building as dwelling for 50 years in Bornholm, Denmark"	50 years	Whole house (restoration and/or renovation)		16	Ecoinvent	Denmark
Arbulu *et al.* [29]	A1–A3; A5; B4; B6	m^2/year of the heated area	50 years	Insulation; window replacement; solar thermal panels, heat		2 – GWP and NRPE		Basque Country
Khadim *et al.* [30]	Cradle to cradle	a single-family residential house with a usable floor area of 95 m^2 (normalized per m^2)	60 years	4 scenarios (for structure, skin, space plan, and services)	CML 2001 baseline	11 midpoint based indicators	Ecoinvent 3.8	Netherlands
Arbulu *et al.* [31]	A1–A3; B4; B6	m^2/year	50 years	Insulation, window replacement, heating system replacement		GWP		Basque Country
Kertsmik *et al.* [32]	A1-A5; B4; B6; C1–C4; D		50 years	A complete comprehensiv e renovation		GWP		Estonia
Luo *et al.* [33]			50 years	Wall, roof, building light remediation, etc.		GWP		China

These methodological foundations contribute to the comparability and reliability of LCA studies in both new construction and renovation contexts.

Building materials and components significantly influence a building's environmental performance throughout its life cycle. Consequently, LCA helps incorporate environmental awareness into selecting sustainable building materials and components. The embodied energy of buildings encompasses the indirect energy used for manufacturing building materials and the direct energy used for on-site construction [35], [36]. An LCA-based module on choosing building materials with less environmental impact would be the next step forward for more sustainable PEDs. Bio-based materials hold the potential to have less environmental impact, due to the CO_2 capture and in some cases the usage of waste products, thus using a circular approach [37].

3.3. Energy Production and Energy Flexibility

Effective mitigation strategies depend on available technology and government policies to transition sectors from fossil fuels to sustainable alternatives [38].

TABLE 3. MAIN CHALLENGES REGARDING ON-SITE ENERGY PRODUCTION

Limitations		**References**
Environmental	Variable outdoor conditions Climate zones	[39], [40]
Economical	High installation costs Long payback periods Existing policies	[38], [40]
Social	Occupancy patterns	[39]
Technical	Building design Rooftop area/ land availability For historic buildings – preserving the historical/cultural appearance by performing reversible, non-invasive, and non-destructive interventions Energy storage systems	[11], [39]–[41]

For residential buildings, three main on-site energy production options are considered: heat pumps, PV panels, and solar collectors. There are LCAs that have been developed for on-site energy production, for example, for a ground-source heat pump [38], as well as solar PV systems [41]. Heat pump LCA case studies indicate that the B1 stage (Use) is the primary contributor, accounting for nearly 80 % of the system's environmental impact [38]. While this highlights the need to focus more on operational emissions, embodied emissions still play a significant role in achieving net-zero emission districts.

Although LCA for on-site energy production and energy storage in buildings has not been as extensively explored in the scientific literature, foundational methodologies do exist and can be applied in such analyses [42]. However, when considering PEDs, the complexity increases significantly due to their larger scale and the greater number of interacting components involved. PEDs integrate multiple energy sources, storage systems, and distribution networks, leading to a more intricate assessment process. Given these complexities, the development of a standardized methodological framework would be highly beneficial. A unified approach to LCA for PEDs would enhance comparability across studies, ensuring consistency in evaluating environmental impacts and improving the reliability of findings. Establishing such a framework would not only facilitate benchmarking between different PED implementations but also support informed decision-making in the transition toward sustainable and energy-positive urban environments.

4. APPLYING LIFE CYCLE ASSESSMENT FOR PED EVALUATION

Defining system boundaries is a key step in conducting an LCA, as it establishes a clear framework for inventory data collection. While collecting data on direct emission sources is often straightforward, and reducing emissions from these sources is typically achievable, compiling an inventory for embodied emissions is significantly more challenging. In many cases, detailed data is either unavailable or limited to generalized averages, requiring numerous assumptions. This, in turn, reduces the overall data quality and makes the results less reliable. Adapted from Berville C. [43] article, the authors propose system boundaries of PED, addressing the main direct and embodied emission sources that should be included in LCA.

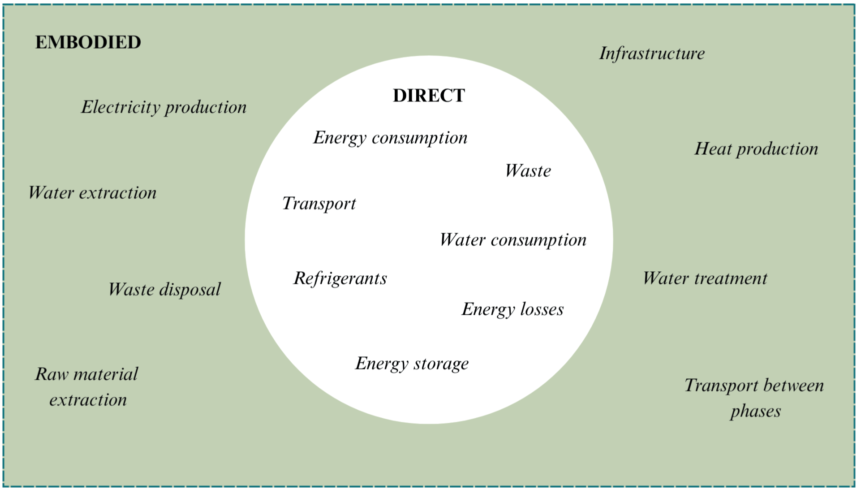

Fig. 3. System boundaries of Positive Energy District.

When defining the functional unit for an LCA in the context of PEDs (PEDs), both time and population can be considered. Dorr E. [44] suggests to base the functional unit on a specific time period, such as one year, 10 years, or even 20 years, depending on the scope and goals of the assessment. This allows for a consistent and measurable comparison of environmental impacts over time. Additionally, the functional unit can be normalized per capita, such as per person living in the district, to reflect the environmental burden or benefit attributed to each resident. This is especially useful for comparing districts of different sizes or evaluating the effectiveness of PEDs in delivering sustainability benefits at the individual level. Selecting an appropriate functional unit is crucial, as it directly influences how results are interpreted and compared across different case studies or scenarios.

5. Research Gaps and Concluding Remarks

While PEDs strive to balance energy production and consumption, the complexity of their life cycle impacts presents significant challenges in fully eliminating emissions. A major limitation in many assessments is the incomplete consideration of all contributing factors, particularly embodied emissions, which account for the environmental impact associated with material extraction, manufacturing, transportation, construction, maintenance, and end-of-life processes. To draw definitive conclusions regarding the feasibility of net-zero emissions in PEDs, a comprehensive life cycle impact assessment should be conducted. This assessment must encompass all relevant aspects, including operational emissions, embodied emissions, and indirect environmental effects related to energy storage, grid interactions, and system dependencies. A more holistic evaluation would provide a clearer understanding of the actual sustainability potential of PEDs and guide the development of more effective mitigation strategies.

Although there are currently no established methodologies or case studies specifically focused on conducting LCAs for Positive Energy Districts (PEDs), numerous case studies related to smart cities do exist. By narrowing the scope and adapting the core principles of existing methodologies, it is possible to develop guidelines for performing LCA in the context of PEDs.

Defining system boundaries and a functional unit are only the initial steps in developing guidelines for conducting LCA on PEDs. However, establishing such guidelines would provide a unified approach, enabling comparability across case studies and supporting the creation of a standardized baseline for evaluation.

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