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Review

Environmental Sustainability Approaches and Positive Energy Districts: A Literature Review

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Abstract: During the last decade, increasing attention has been paid to the emerging concept of Positive Energy Districts (PED) with the aim of pushing the transition to clean energy, but further research efforts are needed to identify design approaches optimized from the point of view of sustainable development. In this context, this literature review is placed, with a specific focus on environmental sustainability within innovative and eco-sustainable districts. The findings show that some sustainability aspects such as sustainable food, urban heat islands mitigation and co-impacts, e.g., green gentrification, are not adequately assessed, while fragmented thinking limits the potential of circularity. In this regard, targeted strategies should be developed. On the other hand, the Key Performance Indicators framework needs some integrations. In this direction, indicators were suggested, among those defined in the Sustainable Development Agenda, the main European standards and initiatives and the relevant literature experiences. Future outlooks should be directed towards: the harmonization of the Life Cycle Assessment in PEDs with reference to modeling assumptions and analysis of multiple impacts; the development of dynamic environmental analyses taking into account the long-term uncertainty due to climate change, data availability and energy decarbonization; the combination of Life Cycle Assessment and Key Performance Indicators based techniques, from a holistic thinking perspective, for a comprehensive design environment and the analysis of the contribution of energy flexibility approaches on the environmental impact of a project.

Keywords: Positive Energy Districts; sustainable districts; Life Cycle Assessment; circular economy; key performance indicators

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1. Introduction

The Sustainable Development Agenda, signed by 193 member countries of the United Nations (UN), defines 17 Sustainable Development Goals (SDGs) which are the basis of a prosperous and healthy planet [1,2]. Some of the major global challenges, expressed by SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SGD 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land), are the development of a fully decarbonized economy and the mitigation of pollution and resource depletion. The need of decarbonization is also highlighted by the International Panel on Climate Change (IPCC), which has studied four possible future scenarios for the emission of greenhouse gases—the "Representative Concentration Pathways" (RCP) [3]. The estimated increase in the average temperature of the planet compared to the pre-industrial scenario is significantly variable among the different scenarios. Thus, in order to keep the average temperature increase below 1.5 °C [4], it is urgent to pave the way for the decarbonization of human activities. Furthermore, climate change mitigation also has repercussions on the social sphere, contributing positively to reducing the number of people in extreme poverty and increasing the potential for creating a more equitable society, that highlight the synergies between the dual goals of keeping the temperature below 1.5 °C global warming and achieving the Sustainable Development Goals [5]. Environmental issues are also deeply within the agenda of the European Union (EU) through the Green Deal [6] and the Energy Performance of Buildings Directive (EPBD) [7]. The Green Deal uncouples the concept of economic growth from the use of resources, promotes circular economy and aims at climate neutrality in 2050 through eco-design. Eco-design is defined as the set of tools aimed at improving the environmental footprint of a product/system [8,9], while the circular economy is based on the idea that the economy can self-regenerate on the basis of strategic mechanisms of reuse, repair, recycling and reduction in the demand for material products as in a closed cycle [10]. These policy actions are focused on the decarbonization of cities, especially considering that 55.7% of the world population is in urban areas [11], promoting the energy efficiency of buildings and the transition to clean energy. In this context, buildings play an essential role in the achievement of sustainable development since the buildings sector contributes approximately by 36% to final energy use and 39% to carbon dioxide emissions on a global level [7,12]. A considerable share of the emissions, equal to 11% [13,14], is embodied in buildings as it is associated with the supply chain of materials and components, while the remainder is attributed to operation. This figure is even more relevant considering that due to climate change, an increase in energy consumption and a worsening of urban heat islands are expected [15,16]. As stated in several relevant regulatory acts and International Energy Agency (IEA) reports, the future direction for buildings is holistic design which includes the improvement of the energy performance of the building envelope, the use of eco-friendly and circular materials and the optimization of renewable energy and the flexible demand control [6,7,12,14,17]. This green revolution in construction can also lead to greater sustainability in industries as a better eco-profile of materials and technologies is needed [17], an increase in the asset value of buildings while creating comfortable spaces and potentially harbingers of greater productivity for workers, and to the reduction in energy poverty by reducing the operating costs [14]. Within the urban context, mobility also requires innovation and efficiency policies as the transport sector accounts for 24% of the world's CO_2 emissions [17]. To date, the transition to sustainable cities is already underway, but the speed and the rate of decarbonization are still insufficient compared to the objectives [13], as in 2018 due to the 1.7% increase in CO_2 emissions [17,18] linked to the raise in the global energy demand [19]. In this regard, the EU's Strategic Energy Technology (SET) Plan defined ten actions to accelerate the transformation underway [20]. Among these, action number 3.2 *"Smart Cities and Communities"*, which is part of action no. 3 *"Create technologies and services for smart homes that provide smart solutions to energy consumers"*, aims to create 100 Positive Energy Districts (PEDs) within 2025 [21]. This perspective aims at optimizing the paradigm of distributed clean energy generation based on prosumerism, exploiting the energy flexibility due to the exchanges of energy between buildings and the local renewable energy sources (RES), according to a path oriented towards sustainable development [22–24]. In fact, the PED acronym indicates an innovative urban district, which, combining high energy performance, RES integration and advanced energy management, presents a positive annual balance between the energy produced and that consumed. The concept of PED arises from the above-mentioned decarbonization and sustainability needs and has two fundamental characteristics [4]:

- Energy security and stability, obtainable through energy efficiency and active demand management strategies (for load shifting and energy peak reduction).
- Sustainability in all its forms to ensure high quality of life for the occupants and safeguard the environment by achieving the objectives of the COP-21.

The concept of PED is also connected to the themes of Citizen Energy Community (CEC) and Renewable Energy Community (REC) defined, respectively, by the Internal Electricity Market EU Directive (IEMD) [25] and the Renewable Energy EU Directive (REDII) [26]. Other interrelated actions are the COST (European Cooperation in Science and Technology) action on Positive Energy Districts, EERA (European Energy Research Alliance) aimed at developing research on PEDs and their extension to the smart city scale and Joint Programming Initiative (JPI) Urban Europe, the European network of agencies aimed at disseminating and financing pilot projects inspired by the PED target.

The scientific community has shown a growing interest in the last decade towards climate-friendly districts, including PEDs [27]. Despite this, it remains to be clearly determined how these concepts can drive sustainable development [28]. As discussed in [29,30], the effective and sustainable design of PEDs requires, due to their innovative characteristics, a systemic and holistic methodological design approach that should take into account technological complexity, environmental compatibility and socio-economic issues. In this context, within the International Energy Agency's Energy in Buildings and Communities Program (IEA EBC) Annex 83 *"Positive Energy Districts"*, Subtask C is aimed at developing environmental, social and economic sustainable paths towards the implementation of PEDs [27].

1.1. Positive Energy Districts: Fundamentals and Definitions

The concept of Positive Energy Building (PEB) derives from of the Net Zero Energy Building (nZEB) concept [31,32]. By extending the scale of the project, in order to exploit the energy mutualization between buildings [33], the concepts of Positive Energy Neighborhood (PEN)/Positive Energy District (PED) are obtained. As discussed within the EU project "COOPERATE" [34], a PEN is *"a neighbourhood which can maximize usage of local and RES whilst positively contributing to the optimization and security of the wider electricity grid"*. As for the definition of net zero energy and positive energy buildings, for the urban agglomerations it is also necessary to specify the metric of the energy balance (primary or final), time period (one operating year or the life cycle, including the embodied energy in the system), boundaries of the study, etc. [31,35,36]. Within the EU SET Plan working group, a PED is defined as *"a district with annual net zero energy import and net zero CO_2 emissions, working towards an annual local surplus production of renewable energy"* [21]. To support the SET plan 3.2, the JPI-Urban Europe has defined a program focused on PEDs [37], within which a framework of definitions is proposed in order to harmonize the concept of PED/PEN [38]. To conceptualize it, three functions are defined: (a) the energy production function, (b) the energy efficiency function and (c) the energy flexibility function. An optimal set of the three functions should be determined for each PED case-study, according to the guiding principles of economic, social and environmental sustainability, inclusiveness and quality of life and in response to local climatic and urban requirements. Function (a) implies the need, for climate neutrality, to exploit the on-site generation of energy from renewable sources to meet the district's energy demand. Function (b) expresses the energy efficiency requirement for reducing energy consumption from a life cycle perspective. Finally, function (c) summarizes the energy flexibility requirement based on demand management and aimed at balancing the energy flows. Besides the JPI, also other frameworks try to complement the existing definitions. In particular, Ala-Juusela et al. [22] proposed a detailed definition, specifying the system boundaries: *"PENs are those in which the annual energy demand is lower than annual energy supply from local renewable energy sources. […] The aim is to support the integration of distributed renewable energy generation into wider energy networks and provide a functional, healthy, user friendly environment with as low energy demand and little environmental impact as possible. […] To avoid sub-optimisation it is key that the wider context is considered in the design and operation of PENs throughout its entire life cycle. Energy demand of a neighbourhood includes the energy demand of buildings and other infrastructures, such as waste and water management, parks, open spaces and public lighting, as well as the energy demand from transport. Renewable energy includes solar energy, biofuels and heat pumps (ground, rock or water), with the supply facilities placed where it is most efficient and sustainable. The transport distance of biofuels must be limited to 100 km"*.

The point of view adopted by the working group of the EU project "syn.ikia" [30] pays particular attention to the correlation between PEDs/PENs and sustainable development and leads to the definition of the concept of Sustainable Plus Energy Neighborhood (SPEN).

According to this vision, a PED/PEN:

- *"couples the built environment with sustainable energy production, consumption, and mobility (e.g., EV charging) to create added value and incentives for the consumers and the society;*
- *makes optimal use of advanced materials, local RES, and other low carbon solutions (i.e., local storage, smart energy grids, demand-response, cutting-edge energy management systems, user interaction, and ICT):*
- *offers affordable living, improved indoor environment, and well-being for the inhabitants."*

Notably, it concerns the calculation of the energy balance of a building district oriented to the PED target, a procedure is presented in [39]. The method developed within the working group of the EU H2020 project "MAKING-CITY" [40] includes: the identification of the boundaries, the calculation of the district's energy demand and finally the calculation of the primary energy balance through Equation (1).

$$\mathrm{BALANCE} = \mathrm{PEI} - \mathrm{PEE} \tag{1}$$

Given the non-renewable primary energy factors ($\mathrm{PEF_{nren}}$), the Primary Energy Imported (PEI) and the Primary Energy Exported (PEE) are calculated according to Equation (2).

$$\begin{cases} \mathrm{PEI} = \sum \text{Delivered energy per energy carrier} \times \mathrm{PEF_{nren}} \text{ per energy carrier} \\ \mathrm{PEE} = \sum \text{Exported energy per energy carrier} \times \mathrm{PEF_{nren}} \text{ per energy carrier} \end{cases} \tag{2}$$

If PEE > PEI, the PED status is obtained. Open questions concern the choice of primary energy factors and the standardized definition of the elements to be included in the balance, with a focus also on mobility, automation devices and household appliances, which are often overlooked. As for the boundaries of the PED, three possible types are defined [30,41]:

- Geographical boundaries: boundaries of the PED identified by spatial limits of the district which include the urban agglomeration.
- Functional boundaries: limits of the PED derived from energy networks, which can also extend over a larger area than the district.
- Virtual boundaries: borders not dictated by graphical limits of the PED but by contractual ties as energy infrastructure of the PED located outside the urban agglomeration (e.g., an offshore wind power plant).

Furthermore, three PED typologies were identified depending on the conceptualization of the district and the energy balance [41,42]:

- Autonomous PED: positive annual energy balance within the geographical boundaries and possible connection with the outside to provide energy and flexibility.
- Dynamic PED: positive annual energy balance within the geographical boundaries with bi-directional exchange of energy with the hinterland, as with other PEDs or with energy networks (import in moments of production deficit or export of energy).
- Virtual PED: positive annual energy balance within the virtual boundaries of the PED with dynamic energy exchanges with the hinterland.

On the other hand, the approach of the "Sustainable buildings and cities" initiative [43], for the development of PEDs in Austria, distinguishes three types of PED on the basis of the system boundaries: PED Alpha, PED Alpha + Mobil and PED Omega. The first type achieved a positive primary energy balance relative to all the energy services of the district except for mobility, which is instead included in the energy balance of the second. Finally, in the third type, the embodied energy in systems and materials is also taken into account.

1.2. Objective of the Study

This paper presents a review of the scientific literature on environmental sustainability approaches specifically devised in PED pilot projects and also in urban contexts which, although they do not achieve a positive energy balance, present several analogies and connections with the concept of PED. In particular, the literature review focuses on the:

- Analysis of the methods and approaches of environmental sustainability in PEDs and in sustainable districts from which lessons learned could be transposed to the PEDs.
- Analysis of the Key Performance Indicators relating to the assessment of the environmental sustainability of innovative sustainable districts.
- Identification of research gaps, hot spots and barriers towards PED development.

The document is structured as follows: Section 2 describes the methodology adopted to carry out a systematic review on the topic; Section 3 presents the results of the work on trends and methods of environmental sustainability, with an in-depth analysis also on indicators, while Section 4 discusses them further. Finally, Section 5 contains conclusions and future perspectives on the subject.

2. Materials and Methods

To carry out a systematic review, the method proposed in [44] for drafting systematic reviews, in the five-step version adapted from Brozovsky et al. [45], is used. In order for the overview of the relevant environmental urban sustainability approaches to be complete, the review is also extended to urban agglomerations which, although not reaching the PED target, show similar models of resource and RES management and environmental/socio/economic objectives and requirements such as Net Zero Energy Districts (NZEDs), Zero Emission Neighborhoods (ZENs) and smart districts particularly oriented towards clean energy and sustainability.

The key research questions are:

1. What are the trends for urban environmental sustainability, and given the interconnected and multifaceted nature of sustainability, have integrated sustainability approaches been sought?
2. Which KPIs are used and what others could integrate the evaluation framework?
3. What are the main challenges that should be addressed in the Life Cycle Assessment (LCA) of PEDs?

Figure 1 represents an overview of the research framework of the literature review.

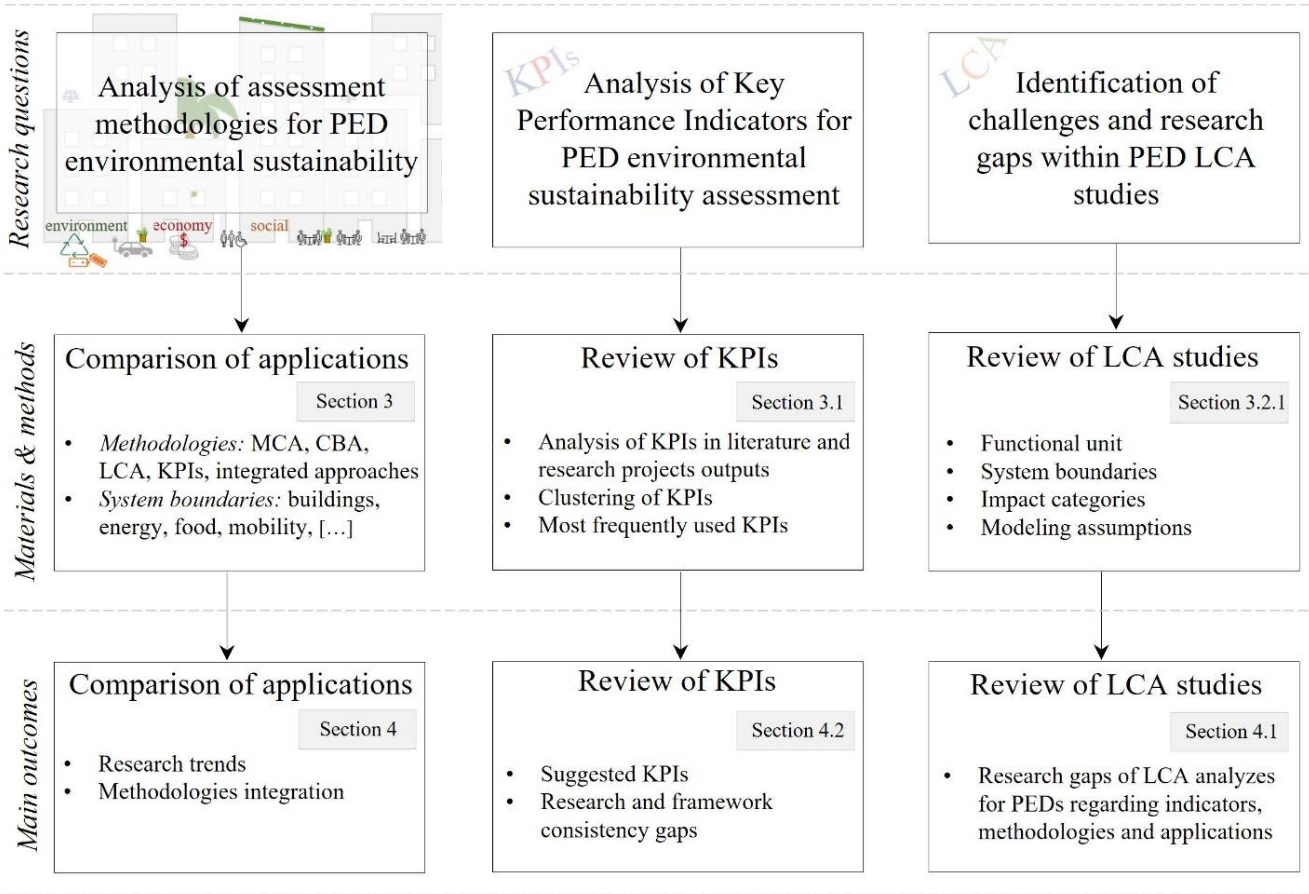

Figure 1. General overview of the research framework. Section 3.1. Review of KPIs; Section 3.2.1. Review of LCA studies; Section 4.2. Review of KPIs; Section 4.1. Review of LCA studies.

The literature analysis was performed in the Scopus database within the search fields article title, abstract and keywords in the period 2013–2021. The keywords used and string combination (iterated for synonyms) are reported below in Figure 2.

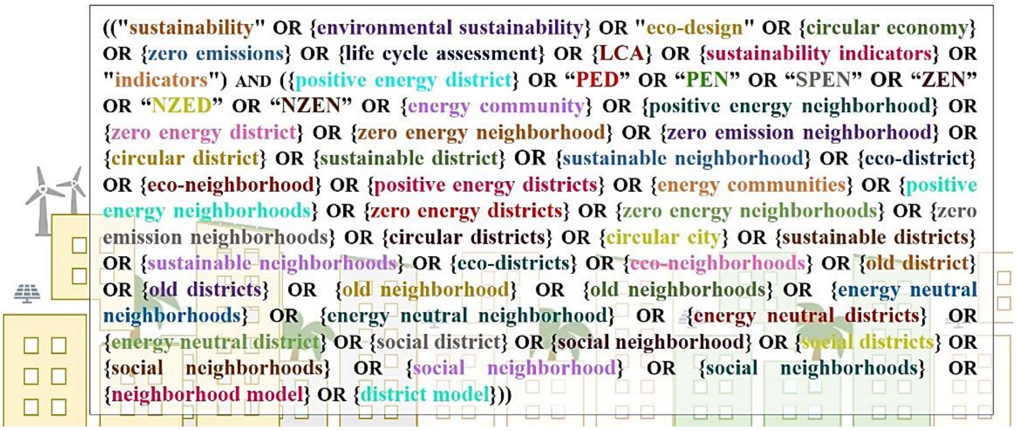

Figure 2. Research database keywords used.

As a result, a total of 301 documents were identified, and their co-occurrence with the papers' keywords is shown in Figure 3.

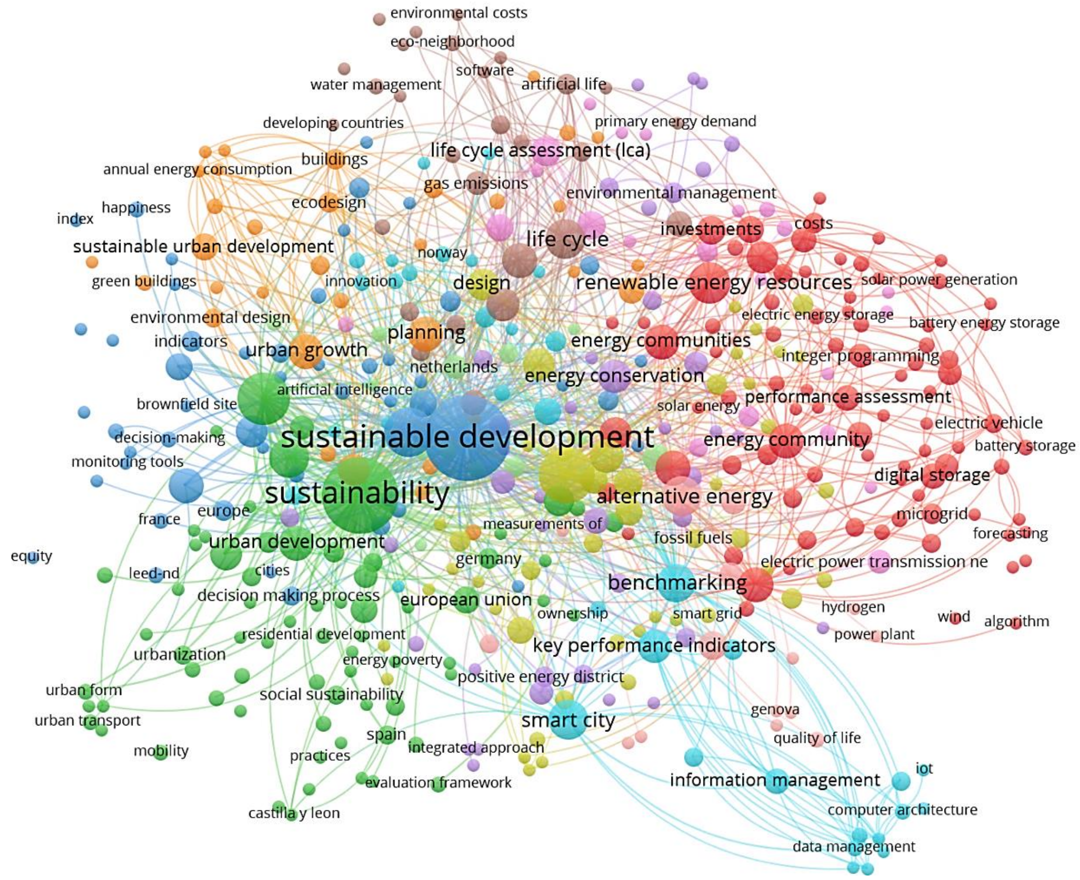

Figure 3. Authors' keywords co-occurrence.

All documents identified were screened and checked for connection with the research topics mentioned. More in detail, the studies that did not adequately fit the objective of the review and the field of study (218 documents) were removed, while the remaining elements were subject to the eligibility check. In the end, 41 documents have been included in this study. The time and journal distribution of the selected documents is shown in Figure 4.

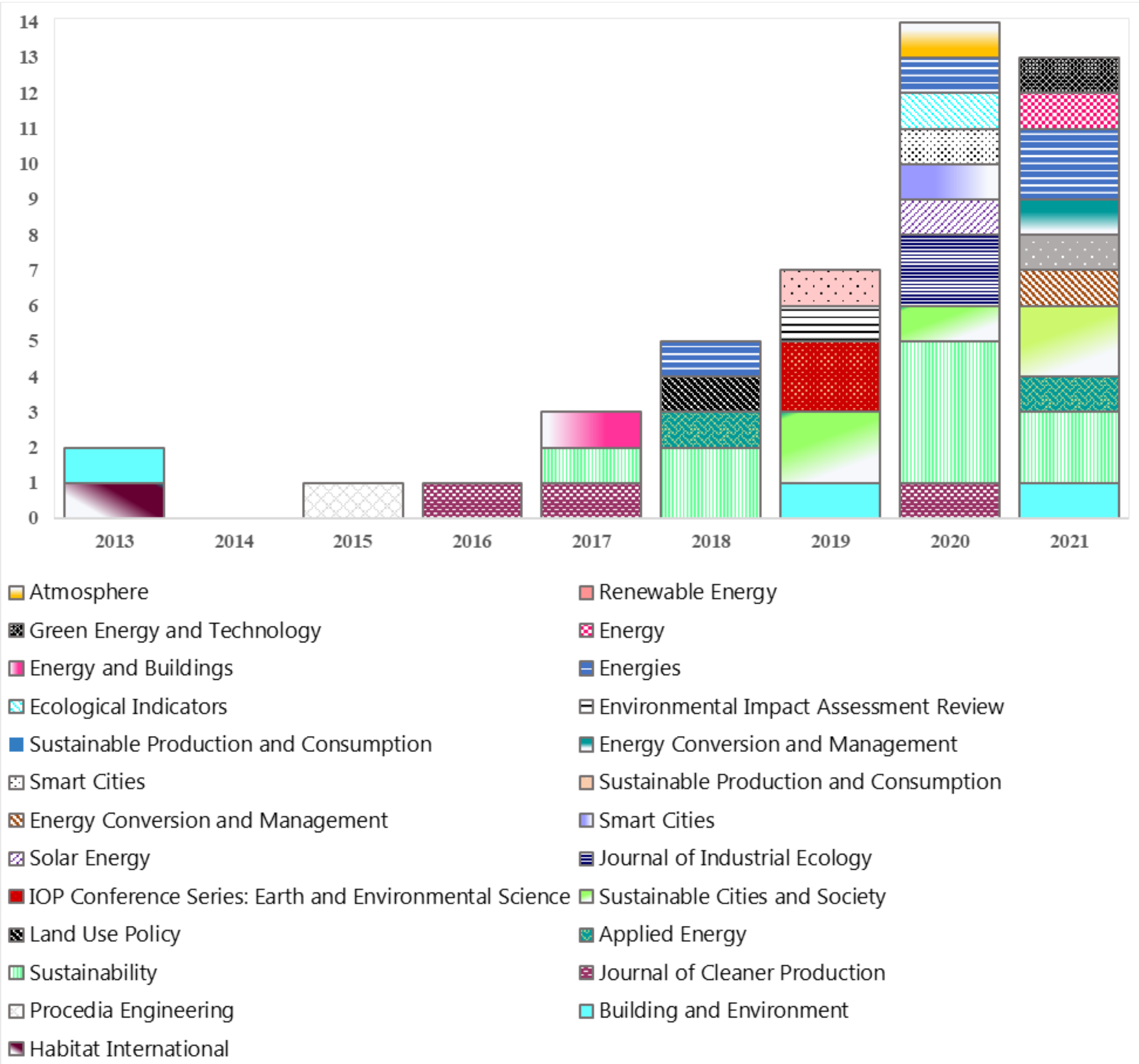

Figure 4. Time and journal distribution of papers included in the literature review.

Moreover and as in [46], the data related to the methodological approaches and to the evaluation of the environmental sustainability of PEDs and similar pilot projects were collected according to the following steps: sorting all the H2020 projects of interest, listed also in the PED Booklet collected by the PED Programme Management of JPI Urban Europe [38], download of relevant technical reports and additional articles recommended from official EU project websites.

The relevant papers and reports of 13 H2020 projects (Table 1), for which the data relating to the sustainability approach/KPIs used are discussed and available, have been included in the state of the art.

Table 1. European smart cities and PED projects with a focus on sustainability.

Project Name and Website	Doc. Ref.	Project Overview	Lighthouse City Location
MySMARTLife [47] *Transition of EU cities towards a new concept of Smart Life and Economy*	[48,49]	Project aimed at the clean energy transition and reduction in CO_2 emissions in 3 lighthouse cities, with an eye towards socio-economic aspects.	Finland, France, Germany.
syn.ikia [50] *Sustainable Plus Energy Neighbourhoods*	[30,51]	Project aimed at creating SPENs, in 4 different climatic locations by developing a highly sustainable design approach in order to combat climate change and social exclusion.	Austria, Netherlands, Norway, Spain.
ATELIER [52] *AmsTErdam BiLbao cItizen drivEn smaRt cities*	[53–55]	Smart city project focused on the implementation of inclusive and sustainable PEDs, where residents are also co-deciders and co-implementers.	Netherlands, Spain.
Smart-BEEjS [56] *Smart Value Generation by Building Efficiency and Energy Justice for Sustainable Living*	[46]	International consortium of universities and research centers aimed at the promotion and development of PEDs, tackling energy poverty through human-centric sustainability practices.	(-)
MAtchUP [57] *Maximizing the Upscaling and replication potential of high-level urban transformation strategies*	[58–63]	Project aimed at designing sustainable and clean energy smart cities by means of social, economic and environmental models.	Germany, Spain, Turkey.
REMO URBAN [64] *REgeneration MOdel for accelerating the smart URBAN transformation*	[65–71]	Project aimed at demonstrating a holistic approach to urban regeneration, based on citizen involvement and energy efficiency measures, in 3 lighthouse cities.	Great Britain, Spain, Turkey.
SmartEnCity [56] *Towards Smart Zero CO_2 Cities across Europe*	[72–76]	Project aimed at converting 3 lighthouse cities into Smart Zero Carbon Cities, centered on the concept of sustainability and prosumerism.	Denmark, Estonia, Spain.

SPARCS [77] *Sustainable energy Positive and zero cARbon Communities*	[78–82]	Project aimed at creating carbon free and PEDs in 2 lighthouse cities with a focus on energy flexibility and sustainability.	Germany, Finland.
REPLICATE [83] *Renaissance of Places with Innovative Citizenship and Technologies*	[84,85]	Project aimed at demonstrating innovative and sustainable smart city solutions with a view to climate change and well-being and co-participation of citizens.	Great Britain, Italy, Spain.
+CityxChange [86] *Positive City ExChange*	[87,88]	Project aimed at the transition towards the PED paradigm of 2 lighthouse cities through an open innovation and zero emissions urban path focused on RES.	Ireland, Norway.
POCITYF [89] *Leading the smart evolution of historical cities*	[54,90,91]	Smart city project aimed at implementing the PED paradigm in 2 historic lighthouse cities, through an eco-model compatible with the cultural value of districts.	Netherlands, Portugal.
MAKING-CITY [40] *Energy efficient pathway for the city transformation*	[54,92]	Project oriented towards low-carbon city planning focused on energy flexibility and sustainability through the experimentation of PEDs in 2 lighthouse cities.	Finland, Netherlands.
COOPERaTE [93] *Control and Optimization for Energy-Positive Neighborhoods*	[32,34,94]	Project aimed at achieving PEN status in 2 campuses by demonstrating energy efficiency, RES optimization and sustainability solutions.	France, Ireland.

All relevant documents are subject to the stage of categorization and analysis. In this last phase, data extracted from the relevant scientific documents were integrated with the detailed and relevant data of the EU projects under review. The elements were then analyzed and categorized according to the approach used and the topics addressed.

3. Literature Review Results

According to the Complexity Theory [95], a city is an ecosystem, characterized by close connections between material flows, resources, inhabitants and knowledge that mutually influence each other, and is the subject of continuous evolutionary processes that lead to new urban balances. Consequently, the design of PEDs is also a complex subject, both from a conceptual and operational point of view, as it refers to a complex system and requires the identification and analysis of the socio-economic and environmental aspects that characterize its sustainability [96].

Sustainable urban planning should also address the uncontrolled urban sprawl and lead to the creation of a stimulating healthy environment, favoring the design of mixed-use districts with high population density and a low environmental impact [1,96–100]. In this regard, a multidisciplinary and holistic approach, proactively participated by all stakeholders, is needed [96].

This section presents the results of the literature review with a distinction within the assessment methods used and the main performance indicators used within it.

Overall, urban sustainability approaches can be classified into three categories from the methodological point of view:

- Applications based on Key Performance Indicators (KPIs) and supported by the optimization/Multi Criteria Analysis (MCA)/Cost Benefit Analysis (CBA), etc.
- Applications based on Life Cycle Thinking (LCT), more specifically on Life Cycle Assessment (LCA).
- Mixed methods that combine LCT techniques with other KPI-based methods.

As for the Multi-Criteria Decision Analysis (MCDA) or Multi-Criteria Analysis (MCA), it includes a wide range of methodologies, based on the definition and analysis of appropriate decision-making criteria, that aim at combining the different perspectives of stakeholders [101,102]. MCA can be applied through many approaches for the aggregation of results [103,104]. The mostly used method is the Analytic Hierarchy Process (AHP) [99,105,106], which is based on the paired comparison of the criteria to determine the weighting factors of the criteria; while the PROMETHEE method is used in [107] and the Hermione methodology in [96]. The approaches differ in the definition and ranking of the criteria used to analyze the sustainability of the proposed urban scenarios. In [108], two different MCA approaches, the MACBETH method and the Playing Cards Method, are compared. The findings indicate that the data processing in the MACBETH approach is not perceived as completely clear and confident by the stakeholders, while the Playing Cards Method is more intuitive and stimulates a more fruitful discussion on the criteria among stakeholders.

Cost Benefit Analysis (CBA) is an analytical method for assessing the economic viability of design alternatives [109–111]. CBA is used, also in green building, to identify efficient resource management programs by calculating the economic benefits of project scenarios in the long term [111–113]. Recently, Becchio et al. [114] proposed a combined CBA-MCA approach in order to tackle the limitations of the CBA due to the difficulty in estimating the monetary values of social and environmental benefits, but further efforts are needed to test the proposed method in a real eco-district. In some applications, further mixed approaches are proposed: i.e., the potential of the integration of MCA with GIS is highlighted in [108] to develop and test a Multicriteria Spatial Decision Support System (MC-SDSS) for the evaluation of alternative energy scenarios.

Life Cycle Thinking-based methods are holistic approaches that aim at the assessment of the impacts of a product throughout its entire life cycle, thus aiming at reducing the use of resources and emissions in air, water and soil while the improvement of its social and economic performance is achieved [115]. The evaluation techniques derived from this approach are the Life Cycle Assessment (LCA), the Life Cycle Costing (LCC), the Social-LCA (S-LCA) and the Life Cycle Sustainability Assessment (LSCA). LCC is an economic evaluation technique that makes it possible to reduce costs in the life cycle of the product [116,117], while S-LCA explores the social impacts [118]. LCA is the methodology for assessing the environmental impacts [119]. Among the applications, LCA is also used in the planning phase of buildings to delve into the life cycle environmental performance [120]. In fact, a high-performance building often requires a high quantity of materials for its construction and plant components, which entail a greater impact during the initial and end of life phases of the building and, then, a greater embodied energy [35,120–

124]. Therefore, to avoid shifting the impacts from the production phase to the other phases of the building life cycle, LCA facilitates the eco-design of building structures [120]. Although the application of LCT to investigate the sustainability of the construction sector is revealing fundamental knowledge [125,126], it could be more widespread by overcoming the difficulties related to data availability and computational effort [127–129]. Moreover, as discussed in [130–132], the urban complexity promotes and needs the integration of LCT with other tools, such as exergetic analysis, CBA and MCA.

Regarding the focus of the environmental analysis, the categories that should be included in the sustainability analysis are buildings and energy, mobility, green spaces, waste, land use, food, etc. [132]. Table 2 provides an overview and characterization of the eco-sustainability approaches available within the state of the art.

Table 2. Sustainability approaches in urban areas: overview and classification of all revised scientific articles.

References		Analysis Details					Sustainability Dimension		
Authors	**Ref.**	**Project**	**Type**	**Type of RES Systems**	**Analyzed Elements**	**Method**	**Environmental**	**Economic**	**Social**
Lausselet et al.	[133]	ZEN	Mixed use	PV panels	Buildings, mobility, open spaces, energy systems	LCA	√	(-)	(-)
Lausselet et al.	[128]	ZEN	Residential	PV panels, thermal solar collectors	Buildings, mobility, energy systems	LCA	√	(-)	(-)
Walker et al.	[134]	NZED	Residential + commercial	PV panels	Energy systems	LCT, MCA	√	√	(-)
Cerón-Palma et al.	[135]	SD	Residential	(n/s)	Energy systems, technology, green spaces, food	LCA, Social surveys	√	(-)	√
Nematchoua et al.	[136]	NZED (1st, 2nd)	Residential (1st), residential + commercial (2nd)	(n/s)	Buildings, mobility, open spaces, energy systems	LCA, Climate change model	√	(-)	(-)
Guarino et al.	[137]	NZED	Residential + commercial + institutional	PV panels, thermal solar collectors (heat storage)	Energy systems	LCA	√	(-)	(-)
Nematchoua et al.,	[138]	NZED (1st, 2nd)	Residential (1st), residential + commercial (2nd)	(n/s)	Buildings, mobility, open spaces, energy systems	LCA	√	(-)	(-)
Nematchoua et al.	[139]	SD	Mixed use	PV panels	Buildings, mobility, energy systems	LCA	√	(-)	(-)

Nematchoua et al.	[140]	SD	Residential	(n/s)	Land use (buildings redensification), water management	LCA	√	(-)	(-)
Nematchoua et al.	[141]	SD	Residential	PV panels	Buildings, land use (buildings redensification), mobility, water, on site energy systems	LCA	√	(-)	(-)
Lausselet et al.	[142]	ZEN	Residential + schools	PV panels, thermal solar collectors	Buildings	LCA, Material Flow Analysis (MFA)	√	(-)	(-)
Lausselet et al.	[143]	ZEN	Residential + schools	PV panels, CHP systems powered by wood chips and district heating	Buildings, mobility, infrastructure, networks, on-site energy systems	LCA	√	(-)	(-)
Lund et al.	[144]	ZEN	Residential + schools	PV panels, CHP systems powered by wood chips (with district heating)	Buildings, mobility, infrastructure, networks, on-site energy systems	LCA	√	(-)	(-)
Lotteau et al.	[145]	SD	Mixed use	PV panels, thermal solar collectors	Buildings, open spaces, mobility	LCA	√	√	√
Palumbo et al.	[146]	SD	Mixed use	(n/s)	Buildings, energy systems, water, waste	LCA	√	(-)	(-)
Hafner et al.	[147]	SD	Mixed use	(n/s)	Buildings	LCA	√	(-)	(-)
Rossi et al.	[148]	REC	(n/s)	PV panels	Energy systems	LCA, Optimization	√	√	(-)
Trigaux et al.	[149]	SD	Residential	(n/s)	Buildings	LCA, LCC	√	√	(-)

Bakhtavar et al.	[150]	NZED	(n/s)	PV panels, biomass, geothermal heat pump	Energy systems	LCA, LCC, Optimization	√	√	(-)
Karunathilake et al.	[151]	NZED	Mixed use	Hydro, biomass, onshore wind	Energy systems	LCA, LCC, MCA	√	√	√
Maranghi et al.	[152]	SD	Mixed use	(n/s)	Buildings, mobility, energy systems, green spaces, food, waste, quality of life (…)	LCA, Urban Metabolism (UM)	√	(-)	(-)
Medved et al.	[153]	N.5 SDs	(n/s)	(n/s)	Buildings, mobility, open spaces, energy systems, green spaces, food, recycle, quality of life (…)	KPI-basedstructural model	√	√	√
Moroke at al.	[99]	N.5 SDs	(n/s)	(n/s)	Land use, economy, mobility, open spaces, green spaces, food, recycle, quality of life (…)	MCA	√	√	√
Pérez et al.	[96]	SD	Mixed use	(n/s)	Land use, buildings, quality of life, mobility	MCA	√	√	√
Lombardi et al.	[108]	NZED	(n/s)	(n/s)	Buildings, energy systems	MCA	√	√	√
García-Fuentes et al.	[154]	NZED	Residential	PV panels, thermal solar collectors	Buildings, energy systems	MCA	√	√	√

Lode et al.	[106]	REC	(n/s)	(n/s)	Energy infrastructure and platforms	MCA	√	√	√
Biianco et al.	[155]	PED	Mixed use	PV panels, thermal solar collectors, onshore wind, hydrogen CHP systems	Energy systems	KPI optimization	√	(-)	(-)
Becchio et al.	[104]	NZED	Mixed use	Biomass	Buildings, energy systems	CBA	√	√	√
Sougkakis et al.	[156]	PED (1st), NZED (2nd)		PV panels, geothermal heat pump	Buildings, energy systems	KPI optimization	√	√	(-)
Cerreta et al.	[107]	SD	Commercial	(n/s)	Land use, waste	MCA, circular economy model	√	√	√
Bracco et al.	[157]	ZEN	University campus	PV panels, thermal solar collectors, geothermal heat pump	Energy systems and ICT, waste, mobility	KPIs, circular economy model	√	(-)	√
Paiho et al.	[158]	SD	Mixed use	Solar energy, biogas, (n/s)	Mobility, energy systems, food	KPIs, circular economy model	√	(-)	(-)
Alvarado et al.	[159]	SD	Mixed use	(n/s)	Waste, sharing economy, resource consumption	KPIs, circular economy model	√	√	√
Su et al.	[160]	SD	Mixed use	(n/s)	Mobility, industrial excess heat, second life energy storage devices	KPIs, circular economy models	√	(-)	(-)

✓, included in the analysis and explained with details in the paper; (n/s), not specified in the paper; (-), not included in the analysis.

The review found that in 54% of the cases, the evaluation of the environmental sustainability is merged with that of social and/or economic sustainability and presented within an integrated evaluation framework. More specifically, besides the environmental aspects, the social dimension is investigated in 40.54% of the cases (15 papers), while the economic dimension is in 48.65% of the studies (18 papers). To investigate environmental issues, in 56.76% of cases LCA is used and in 37.84% other methods are used based on KPIs. Among the latter, the application of MCA is prevalent, while for 5%, specific circular economy scenarios are studied in depth. Some research is based on the integration between LCT-MCA, LCA- LCC, LCA and optimization technics, LCA-LCC and optimization and finally LCA-LCC and MCA. As an example, in [134], the authors combine LCA with a multi-criteria matrix in order to facilitate the decision-making process. The identified criteria are:

- Threat of the operational feasibility of the technologies;
- Technical maturity of the energy technologies;
- System reliability;
- Resource feasibility;
- Acceptance of people;
- Institutional/technical/finance/political and regulatory barriers;
- Technical/finance/energy market/environmental/political and regulatory barriers.

In [151], an LCA-LCC tool is combined with MCA for the development of a fuzzy and life cycle perspective on multi-criteria decision making. The method is used in a NZED for the design of the optimal energy system configuration. MCA allows the identification of requirements and stakeholder priorities and other social and logistic issues and benefits (such as local job creation and impact on human health), while the life cycle impacts are analyzed through LCA and LCC.

Maranghi et al. [152] describe a proposal for integration between Urban Metabolism (UM) and LCA. UM is a well-developed concept for the development of smart district [161,162] that relies on the analysis of energy, resources and materials flows (inputs, outputs, storages) in the urban environment. While UM is applied to the district-city scale, LCA, which requires a greater degree of detail also regarding the data, is used for a lower-scale study. The model comprises the sub-sections: energy (inputs: energy sources, energy consumption […]), materials (inputs: water consumption, rainwater, waste recycling […]), transport (inputs: fuel consumption, transport modes […]), governance (inputs: no. of local energy distributors, no. of electric vehicles, policies […]), information (inputs: digital interaction with institutions, urban open data availability […]), and quality of life (inputs: unemployment rate, particulates PM […]),. Using the UM, sub-sections are interrelated according to a functional relationship scheme, while LCA is used for specific systems.

On the other hand, in the revised EU H2020 projects, the evaluation framework is based on the assessment of KPIs, while LCA is also used only in two projects. MCA supports the analysis in syn.ikia and the Eco-Acupuncture technique in POCITYF, together with the use of the TIPPING approach [163] aimed at raising awareness on the need for political adaptations and training governments towards eco-innovation.

3.1. Key Performance Indicators for Sustainable Urbanization

Frameworks of Key Performance Indicators (KPIs) are widely used for the evaluation of urban sustainability [164]. A KPI is defined as *"a quantifiable measure used to assess the success of an organization, an employee,* etc. *in achieving performance goals"*, and unlike an indicator, a KPI is always related to a specific goal [165] and is informative about the degree of achievement of the targets [166]. Initiatives such as the Smart Cities Information System (SCIS) [167], CITYkeys [168] and CONCERTO [169] were created, which have developed interaction platforms and a database of KPIs [165,170–173] in order to favor the exchange of know-how in Europe. The KPIs developed by SCIS mainly refer to the techno-economic aspects of urban design (36 KPIs related to the themes: environment, economy, mobility, energy). The KPIs defined by CITYkeys also consider social and environmental issues (101 KPIs grouped into categories: people, planet, prosperity, governance and propagation), such as those proposed within the CONCERTO working group. KPIs are also defined in the European standards ISO 37120: 2018 (65 KPIs, categories: economy, environment, energy, mobility and governance) and ISO 37122: 2019 (52 KPIs, categories: economy, environment, energy, mobility and governance) and by the United Nations in the Sustainable Development Agenda [2]. These indicators are explicitly related to the Sustainable Development Goals (SDGs) (231 KPIs categorized into the themes of the SDGs).

Key performance indicators are widely used in the context of EU H2020 projects. In the case of already existing urban agglomerations, the KPIs are used to evaluate the environmental performance of the district in its current state and in the developed energy and sustainability retrofit scenarios. Table 3 reports an overview of the categories of KPIs used within the reviewed projects outputs.

Table 3. Overview of the categories of KPIs used within the reviewed EU H2020 projects outputs.

Project	Number of KPIs	Categories
MySMARTLife	151	Urban infrastructures, energy and environment, mobility and transport, citizens, economy and governance
syn.ikia	44	Energy and environmental performance, indoor environmental quality, economic performance, social performance, smartness and flexibility
ATELIER	40	Energy and environment, mobility, social and economy
MAtchUP	188	Efficiency in buildings, urban platforms and ICT, mobility, citizens and society
REMO URBAN	60	Urban organization, environment and resources, citizens and society
SmartEnCity	149	Technical, environmental, economic and social
SPARCS	29	Energy, technological, economic and social
REPLICATE	56	Energy and environment, governance, mobility, infrastructure, social and economy
+CityxChange	33	Energy efficiency, economic, social and regulatory
POCITYF	91	Economy, environment and society–culture
MAKING-CITY	20	Energy and environment, mobility, governance and society–citizens
COOPERaTE	8	Energy

The indicators relating to the broad theme of environmental sustainability have been selected and summarized into thematic sub-classes in Table 4. Where the KPIs overlap with the KPIs defined within the main European standards (ISO 37120: 2018, ISO 37122: 2019), initiatives (SCIS, CITYkeys, CONCERTO) and the UN Sustainable Development Agenda (SDG indicators) are also highlighted.

Table 4. Overview of the environmental-related KPIs used in the revised EU H2020 projects outputs.

Key Performance Indicator	Project	Standard/Initiative
	Clean energy	
Value and/or reduction in the final/primary thermal/electrical energy consumption per year (total and per sector)	POCITYF, REPLICATE, MAtchUP, mySMARTlife, SmartEnCity, ATELIER, SPARCS, REMO URBAN, COOPERaTE	SCIS, CITYkeys, SDG indicators, ISO 37120:2018
Degree of final/primary energy self-supply by RES	POCITYF, REPLICATE, MAtchUP, mySMARTlife, +CityxChange, SmartEnCity, ATELIER, syn.ikia, SPARCS, REMO URBAN, COOPERaTE	SCIS, CITYkeys, SDG indicators, ISO 37120:2018
Self-sufficiency/generation/consumption ratio	POCITYF, +CityxChange, syn.ikia, SPARCS	-
Energy savings	POCITYF, mySMARTlife, ATELIER, SPARCS, COOPERaTE	SCIS, CITYkeys
Increase in installed RES storage capacity	+CityxChange	-
Increase in new RES system integration	+CityxChange	-
Increase in local renewable energy production	MAtchUP, mySMARTlife, +CityxChange, SPARCS	SCIS, CITYkeys,
Heat recovery ratio (thermal energy provided by the heating recovery system ÷ thermal energy consumption)	POCITYF, mySMARTlife	-
Renewable thermal and electrical (certified green) energy generated divided by consumed total energy	SPARCS	-
Charging capacity managed (no. and power of charging points for electric vehicles subjected to an energy demand management)	mySMARTlife	-
No. of organizations with new sustainable energy approaches	+CityxChange	-
Use of waste heat	SPARCS	-
	Comfort	
Indoor air temperature	SmartEnCity, ATELIER, syn.ikia	-
Internal relative humidity	SmartEnCity, ATELIER, syn.ikia	-
Internal air speed and distribution	SmartEnCity	-
Thermal comfort	SmartEnCity, REMO URBAN	-
Indoor air quality	REMO URBAN	-
Outdoor air temperature	ATELIER	-
Predicted Mean Vote (PMV)	syn.ikia	-
Predicted Percentage Dissatisfied (PPD)	syn.ikia	-
Noise pollution	POCITYF, REPLICATE, MAtchUP, ATELIER, syn.ikia, REMO URBAN	CITYkeys, ISO 37120:2018
Illuminance/daylight factor inside and/or outside the buildings	syn.ikia	-
	Climate change and pollution	
Total value and/or reduction in greenhouse (CO_2) gas emissions	POCITYF, REPLICATE, MAtchUP, mySMARTlife, +CityxChange, ATELIER, syn.ikia, SPARCS, REMO URBAN	SCIS, CITYkeys
Carbon dioxide emission reduction	POCITYF, REPLICATE, mySMARTlife, +CityxChange, SmartEnCity, syn.ikia, SPARCS	SCIS, CITYkeys
Total value and/or reduction in NO_x/tHC/$PM_{e\text{-}2.5}$ air pollution	+CityxChange, ATELIER, SPARCS, REMO URBAN	CITYkeys, SDG indicators, ISO 37120:2018
Air quality index	POCITYF, MAtchUP, +CityxChange	CITYkeys
Climate resilience strategy	POCITYF, REMO URBAN	CITYkeys, SDG indicators

Waste and water management		
Municipal solid waste	POCITYF, REPLICATE, REMO URBAN	CITYkeys, ISO 37120:2018
Recycling rate of solid waste	POCITYF, REPLICATE, REMO URBAN, MAKING-CITY	CITYkeys, ISO 37120:2018
Total water consumption	ATELIER, REMO URBAN	CITYkeys, ISO 37120:2018
Percentage of population with water and potable water supply service	REMO URBAN	SDG indicators, ISO 37120:2018
Percentage of the wastewater receiving treatment	REMO URBAN	CITYkeys, SDG indicators
Percentage of households with smart water meters	REMO URBAN	ISO 37122:2019
Percentage of households with drainage system management	REMO URBAN	-
City water monitoring	REMO URBAN	-
Sewage systems management	REMO URBAN	-
Sanitation services	REMO URBAN	-
Sustainable mobility infrastructure		
No. of electric vehicles (EVs) and low-carbon emission vehicles deployed in the area	POCITYF, REPLICATE, MAtchUP, REMO URBAN	SCIS, ISO 37122:2019
No. of electric vehicles (EVs) per capita	REPLICATE, MAtchUP	-
Percentage of electric vehicles (EVs) per private/public/commercial sector	MAtchUP, SPARCS, REMO URBAN	-
Availability rate of e-buses (percentage of days in which the e-buses are available to provide transportation service)	mySMARTlife	-
Vehicle-To-Grid (V2G) parking places (car and bicycle)	SPARCS	-
No. of electric vehicle (EV) charging stations	SPARCS, REMO URBAN	SCIS
No. of solar-powered Vehicle-To-Grid (V2G) charging stations deployed in the area	POCITYF, REPLICATE, MAtchUP, mySMARTlife	SCIS
Share of electric vehicle (EV) demand covered by local RES	ATELIER	-
Access to vehicle-sharing solutions (no. of vehicle for sharing ÷ total population)	MAtchUP	CITYkeys
Access to bike-sharing solutions (no. of bikes for sharing ÷ total population)	MAtchUP	-
Public infrastructure promoting low-carbon mobility	MAKING-CITY	-
Sustainable mobility performance and use		
Availability rate of the solar roads (percentage of time that the solar roads are functioning properly to produce electricity)	mySMARTlife	-
No. of recharges per year (biogas and electric vehicles)	mySMARTlife, SmartEnCity	-
No. of recharge sessions per year (biogas and electric vehicles)	mySMARTlife	-
Annual energy delivered by electric vehicle (EV) charging points	POCITYF, MAtchUP, mySMARTlife, ATELIER, SPARCS, REMO URBAN	-
Annual energy delivered by electric vehicles (EVs) and biogas charging points	SmartEnCity	-
Shared electric vehicles penetration rate (no. of electric vehicles that operate in the platform and in community car-sharing concept)	POCITYF, mySMARTlife, SPARCS	-
Clean mobility utilization	POCITYF, +CityxChange	SCIS
Modal spit (shares of different modes of transportation) and improvement towards non pollutant mobility habits	ATELIER, SPARCS, MAKING-CITY	SCIS
Percentage modal shift from fossil-fuel vehicles to electric vehicles (vehicles/bikes)	+CityxChange	-
Yearly kilometers of shared vehicles	POCITYF	-
No., percentage and duration of deliveries operated with clean vehicles	mySMARTlife	-
No. of annual passengers of electric buses	mySMARTlife	-
Average no. of electric buses passengers per working day	mySMARTlife	-

Targeted share of bicycle and pedestrian mobility mode	SPARCS	-
Environmental sustainability and society		
Residents' energy awareness	SmartEnCity, syn.ikia, SPARCS	-
Economic incentives to promote sustainable actions	REMO URBAN	-
Progress towards energy citizenship	ATELIER	-
Active/pro-active behavior of citizens (e.g., willingness to invest in energy savings measures or pay more for RES or service)	mySMARTlife	SCIS
No. of innovation labs	+CityxChange	-
Citizen engagement in climate-conscious actions	MAKING-CITY	CITYkeys
Environmental awareness	SmartEnCity	-
Urban compactness	REMO URBAN	-
Green areas	REMO URBAN	ISO 37120:2018

The set consisting of a total number of 81 indicators contains the 16% (n.13 KPIs) and 19.75% (n.16 KPIs) indicators defined, respectively, also in the context of the SCIS and CITYkeys initiatives; the 7.41% (n.6 KPIs) indicators overlapping with SDGs; and finally, the 9.88% (n.8 KPIs) and 2.47% (n.2 KPIs) indicators derived also from the ISO 37120: 2018 and ISO 37122: 2019 standards.

The most frequently used KPI area is based on the mitigation of climate change (CO_2 emissions reduction) and the transition to clean energy (energy self-supply by RES). On the other hand, sustainable urban design should also be oriented towards identifying strategic plans for circular production and consumption, through the optimization of energy and resources flows, the preservation of the natural environment and species, the mitigation of all environmental issues and the creation of added socio-economic value along the value chain for a high quality of life for all [21].

In this regard, the most frequently implemented actions to improve the circularity of the district regard: (a) the electrification of the transport system combined with the exploitation of renewable energy management and production technologies and (b) the environmental efficiency in the use of resources and waste. Among the KPIs presented in Table 4, the following indicators have specific connections with the quantification of circularity and the evaluation of targeted scenarios:

- Sustainable mobility KPIs relating to the planning and design of the transport network and infrastructures, such as: no. of electric vehicles (EV) and low-carbon emission vehicles deployed in the area and availability rate of e-buses, Vehicle-To-Grid (V2G) parking places, no. of EV charging stations and solar powered V2G charging stations deployed in the area.
- Mobility performance KPIs aimed at monitoring and assessing the effectiveness of the mobility model during the year and also aimed at identifying potential problems and corrective actions: percentage of time that the solar roads are functioning properly to produce electricity, share of V2G to the total energy system performance, no. of biogas and EV recharges per year and sessions, annual energy delivered by EV charging points, no. of e-vehicles that operate in the platform and in the community car sharing concept and utilization, no. of annual passengers using the new vehicles and/or infrastructure, yearly km of shared vehicles.
- KPIs for sustainable resource management: municipal solid waste, recycling rate of solid waste, percentage of the wastewater receiving treatment, sewage systems management, thermal energy provided by the heating recovery systems, use of waste heat.

On the other hand, some aspects of sustainability and impact categories, such as the contribution of food to circularity and sustainability of the district, are taken into consideration to a lower extent. Besides the EU H2020 experiences, some relevant literature studies have addressed the issue and proposed assessment methods and tailored KPIs. In this context, Moroke et al. [99] also pays attention to sustainable food within the sustainability model, called the *"Successful Neighborhood Model"*. The approach is multi-criteria with a structure that integrates the three dimensions of sustainability, embracing all relevant issues: from sustainable transport and morphological elements to the happiness of residents.

For each criterion, a set of KPIs is defined. With regard to food, the properly defined KPIs are:

- Number of households involved in food production ÷ total no. of households;
- Number of community functional food production projects ÷ no. of community functional food production projects in all neighborhoods.

Medved [153] addresses the issue further, proposing the following KPIs:

- Number of urban food gardens;

- Synergy with local farmers (percentage of people involved in the local food cooperative);
- Number, variety and size of local food cooperatives;
- Initiatives to prevent commercial food chains in the neighborhood.

These KPIs are part of the proposed planning framework, the *"Structural model of Autonomous Sustainable Neighbourhoods"*. The structural model arises from a comparative study, based on direct interviews with stakeholders, of the strategies implemented in the five most sustainable neighborhoods of Europe, which the author visited for the purpose of the research. The model is interdisciplinary and is structured in four sections, the *"pillars of urban sustainability"*. Each pillar encompasses different goals, called *"strategic urban sustainability goals (SUSGs)"*. To evaluate the performance of each urban design alternative in relation to the objectives, or to compare the sustainability of different neighborhoods, the *"sustainability indicators"* are defined. Among these, Medved [153] introduces further circular economy KPIs that could complete the framework on the topic, paying attention also to the ecological footprint of construction materials and to the management of resources and energy in buildings:

- Innovative concepts to reduce resources depletion (biogas from compost, vacuum toilets, per capita material recycling rate, etc.);
- Reduction in water consumption by managing black, grey and rainwater (per capita water consumption, rainwater capture rate);
- Initiatives to reduce solid waste (per capita rubbish production);
- Mandatory energy standards for the retrofit of wasteful buildings;
- Use of ecological building materials (percentage of neighborhood buildings built with natural materials);
- Percentage of energy-efficient buildings (characteristics: energy-positive, smartness, adequate ventilation and insulation, sustainable use of water, recycled materials, passive solar energy utilization, acoustic comfort).

Other authors [157] also defined useful KPIs:

- Rainwater collection;
- Improvement in waste collection;
- Smart garden irrigation system and vertical hydroponic garden.

Although some authors define sets of KPIs with some environmental indicators that could complete the framework of the KPIs used in the pilot projects, in most cases the greenhouse gas emissions and the energy consumption indicators are the only one used.

To overcome this gap, some authors introduced the Ecological Footprint KPI in the set of indicators [154].

However, in a broader perspective, it should also be kept in mind that in the design of environmental sustainability practices for innovative urban districts such as PEDs, it is also necessary to envisage measures to combat the social problems that could arise as a co-impact, such as green gentrification [28,174]. Green gentrification is characterized as the occupation by more affluent social groups of urban areas subject to redevelopment induced by the pursuit of an environmental ethics, which, due to the increase in real estate value, determines the migration and marginalization of the original occupants with lower income [175,176]. In this regard, sustainable PEDs should be developed within a keen socio-economic development focus, avoiding the alienation in the suburbs of the low-income residents through a sustainable and integrated transport system and other actions aimed at social equity [1,30].

In order to integrate the assessment of social and environmental co-impacts into the approach, the concept of *co-benefit*, such as pollution reduction, new *green* jobs creation, comfort improvement, asset value increase, etc., and the consequent monetization of the co-benefits have been introduced for CBA applications in building districts [104,177,178] or taken into consideration in MCA applications and within the KPIs framework. Despite this, the correlation between the phenomenon of green gentrification and environmental sustainability practices should be further analyzed also through specific indicators.

Some KPIs have been defined based on this need:

- Affordability of housing (syn.ikia);
- Average price for buying an apartment per square meter (MAtchUP);
- Housing cost overburden rate: percentage of the population for which the cost of housing represents more than 40% of disposable income (MAtchUP, MAKING-CITY).

In this context, KPIs related to the link between education and environmental awareness could be useful to guarantee long-term sustainability and stimulate circular actions by citizens. Synergy with schools and cultural centers should be part of the urban project to educate young people and create an emotional bond towards sustainability issues. In this regard, the SDG indicator "education for sustainable development" and/or the KPI defined within the CITYkeys initiative: "percentage of schools with environmental education programs" are recommended.

3.2. Environemntal Sustainability Actions and Findings

As for the type of interventions planned in the district sustainability scenarios, energy redevelopment strategies for buildings are the most common in the literature studies and in the EU H2020 ongoing projects. The actions concern: insulation of the building envelope, replacement of windows, efficiency of the SH and DHW production system and the exploitation of on-site RES mainly based on PV systems installation. As an example, Palumbo et al. [146] delve into district redesign scenarios based on the insulation of the building envelope and the replacement of windows, the efficiency of lighting-water appliances and waste management from a life cycle perspective. Compared to the base case, results indicate a global CO_2 emissions reduction of 43% associated with the buildings operation. Global Warming Potential (GWP) also decreases based on the efficiency of public lighting in open spaces (41% reduction).

As part of the ongoing SmartEnCity project, LCA is used with the aim of assessing the environmental impact of the energy retrofit scenarios based on the insulation of the building envelope, replacement of windows and implementation of a biomass district heating network, while in ATELIER, the insulation of the building envelope, the installation of green roofs, triple glazing and a waste-to-energy plant are evaluated.

Specific re-densification strategies in low density districts are, instead, analyzed in [96,100] by means of KPIs and in [128,140,141] through LCA, while heat islands mitigation is delved into in [146] from a life cycle perspective. Redensification approaches include vertical densification (adding a floor to existing buildings) and horizontal densification (designing new buildings). The results are in line in suggesting the first solution, as it generates a lower environmental impact. In [141], a sensitivity analysis of the LCA impact is also developed as the orientation of the buildings changes, which shows a limited impact on the results. Furthermore, in [157], circular thinking is applied to the management of rainwater, suitably filtered and reused for gardening and flushing.

Circular economy strategies are also applied in [107,158–160,179,180], by means of the implementation of circular models supported by KPIs, and in [136,138,140,141,143,147] through LCA. As discussed in [12,14,120,181,182], the life cycle perspective could facilitate the identification of best practices as a glance only at the operational phase could be misleading and lead to a biased assessment. While at the district scale the scientific literature is more limited but growing, at the building level several authors have adopted LCT as a decision-making and investigative aid. For example, Sierra-Pérez et al. [183] use LCA as a guiding tool for the eco-design of a building, identifying glass wool as the most environmentally friendly choice among many types of insulation. Tumminia et al. [184] found that the materials production phase contributes 70–90% of the environmental impact of the life cycle of the building examined and predominates over the operational phase, which is often the most impactful [36,126]. Thiers et al. [35] evaluated the environmental impact of two positive energy buildings for different plant scenarios. The results of the study indicate the building characterized by the most positive value of the primary energy balance is the most eco-sustainable, for almost all of the indicators. The ecotoxicity and human health indicators, due to the high incidence of the production and demolition phases, are instead in contrast with this thesis and highlight the need for materials with a better eco-profile. The life cycle approach is also used in [185] to assess the environmental impact resulting from the use of phase change materials (PCM) in buildings. Although, on the one hand, the use of PCMs is of interest for high-efficiency buildings applications, on the other hand, these materials have a high embodied energy. The study shows that the reduction in the operational impact of the building predominates over the increase in the production and end-of-life phases and leads to a reduction in the environmental impact of the building's life cycle by 10%.

In the LCA applications at the district scale, the implementation of rainwater recovery systems and in some case of permeable floors is a common solution. In this context, the benefits associated with the use of more permeable floors and the exploitation of rainwater recovery systems for the irrigation of green spaces, the cleaning external environments and the operation of the washing machine and toilet are evaluated in [136,138,141]. As a result, the efficient management of rainwater contributes to about 10% of the improvement in the impact categories examined (in particular the production of waste, eutrophication, acidification and damage to human health) [136,138], while according to [140,141] eutrophication is reduced respectively by 32% and 33.6%.

In relation to the further comparison of the results, since the size of the urban district and the population density vary significantly between the studies available, it is necessary to compare common environmental impacts, e.g., CO_2 emissions per inhabitant or per square meter. However, in many cases, not all the information for the geometric and demographic characterization of the district case-study is available, and this makes comparison between findings difficult. According to [127], the GHG emissions of a sustainable district are in the range of 11–124 $kgCO_2/m^2$. Results of the LCA experiences, for which these data are available, can be traced as per 35 $kgCO_2/m^2$ [141], 21.2 $kgCO_2/m^2$ [133], 39.67 $kgCO_2/m^2$ [140] and up to 66.1 $kgCO_2/m^2$ in [128].

In the general framework of LCA experiences, most of the overall emissions are due to buildings and transport. For example, in [133], buildings contribute 52%, of which 91% is due to SH and DHW production (while buildings materials are at 30% in [145]), to the district's GHG emissions, while mobility accounts respectively for 40% and 43% and 61% in [133] and [143,145].

In this context, since sustainable mobility is essential to obtain the PED/ZEN status and in general to achieve the district sustainability goals, approaches based on the development of the electric mobility powered by RES and the diffusion of car sharing solutions are at the basis of all EU H2020 projects. In order to encourage sustainable mobility, car parking restrictions are adopted in [161], while in [143] car sharing and electrification scenarios for mobility are designed from an LCA point of view. The results indicate a reduction in GHG emissions of up to 43% and less need for new road infrastructure. Instead, as found in [143], car sharing solutions reduce the overall environmental impact by 12%.

Overall, LCA could facilitate the transition to a circular economy by supporting the eco-design of technologies and buildings, but as it is highlighted in [186], effective design strategies that facilitate the subsequent disassembly and reuse-recycling of components are required.

Inspired by the principles of the circular economy, Cerón-Palma et al. [135] deal with local production of food using LCA, defining new green spaces in the improvement scenario within the district. Therefore, unlike other similar studies, the CO_2 emissions avoided through the local cultivation of vegetables, in common areas and on the roof, instead of their import from territories outside the urban area, were also evaluated. The results show that the annual reduction in CO_2 emissions is equal to 1.06 tons, 34% of which is associated with energy appliances and systems, 24.5% with green areas and 8.4% with local production of vegetables.

Hafner et al. [147], instead, applied LCA with the aim of comparing the impacts of different construction materials in buildings. Results highlight the importance of eco-friendly materials, such as wood, showing a storage of 12.5 million kg of CO_2 in the wooden constructions for the entire life of the district (50 years).

More comprehensive case studies of circular urban districts are designed by Paiho et al. [158] and Su et al. [160]. Paiho et al. [158] seek circularity solutions for the sustainable redesign of an urban district located in the city of Espoo, demonstration site of the PED project SPARCS. Actions include share electric mobility, heat recovery from a data center and a wastewater treatment plant, local food production (cultivation of tomatoes within the district) and the concept of "*energy as a service*", which supports decentralization and the provision of energy flexibility services. To model the evolution of the economy, the authors developed Business Model Canvas (BMC)-type business models inspired by circularity [187]. In the food scenario, the value proposition of the circular solution is the production of local tomatoes with zero CO_2 emissions and the simplification of the logistics of the production chain. The specific value proposition for the stakeholders (local producers of fertilizers, energy, etc.) is mainly the improvement of the sustainability of the product, while for the users, it is the possibility of employment and other social benefits. Finally, among the resources are the knowledge of tomato cultivation practices and the involvement of customers, while the risks are to be found in the competition with the production of biogas. In the case of shared electric mobility, the value proposition is defined as system flexibility, brand advertising, etc., for stakeholders (among them: the municipality, producers and suppliers of electric vehicles and infrastructure for recharging and logistics), as well as in general a more efficient use of resources and a more inclusive mobility, also with respect to the needs of the population with limited physical abilities. The results show a 50% reduction in transport energy consumption with a 10% decrease in emissions production. The use of waste heat satisfies 58% of the thermal energy demand and local food production guarantees 6% of the total quantity required. On the other hand, Su et al. [160] explore an urban circular economy scenario based on:

- The use of high-temperature industrial waste, from steel industries, in textile and printing industries with lower temperature heat demand and in buildings as a source of district heating and domestic hot water in a perspective of industrial symbiosis;
- The potential of transport electrification, in an energy scenario of high electrical penetration of RES, to decarbonize the sector and contribute to the electricity grid balance;
- The contribution to the circularity of the economy of the reuse of electric car batteries as Battery Energy Storage Systems (BESS) in buildings (although over time the performance becomes inadequate for transportation, it is still suitable for use in more stationary applications).

The study shows that, compared to the reference base case, energy consumption is reduced by 34% while emissions by are reduced 40–43% (energy: 7.1 Mtoe, CO_2 emissions: 14.5 Mt, PM2.5 emissions: 592 t). In the context of circularity, Alvarado et al. [159] highlight the need for more efficient systems for recycling materials and eco-design of products, business models oriented to the sharing economy based on industrial symbiosis, and reduction in material consumption by the inhabitants through re-education for reuse and repair. In this regard, models of industrial symbiosis and circular economy through specific waste management tools and the use of incentives for separate collection, the use of second-life BESS and the adoption of circular building practices are tested in the POCITYF project [91].

Within these topics, the scientific community and society experts have shown a growing interest in the potential of sharing economy and advanced energy management models to facilitate the clean energy transition and the achievement of environmental sustainability goals. Among these, peer-to-peer (P2P) platforms for the management of energy flows could contribute to improving the energy-environmental efficiency and energy flexibility of the district, facilitating "*horizontal*" energy transactions between prosumer citizens [188]. This sharing model is suitable for the PEDs, and if exercised in a socially equitable way, it can be a promoter of the democratic participation of all stakeholders in energy issues and the empowerment of citizens. In this regard and within the EU H2020 projects, specific and tailor-made interventions are developed and evaluated through KPIs. For example, in POCITYF and SPARCS, P2P transactions support a greater perception of prosumers regarding energy control, facilitating the achievement of the project objectives. Furthermore, the P2P model encourages citizens to be promoters of sustainable operating practices through reward tokens.

P2P schemes could be optimized by the use of digital twins that facilitate the sharing of locally produced energy [189]. Digital twins are digital models, based on big data in real time, which could optimize the functioning of the PEDs. Zhang et al. [189] explore the potential of digital twins to enhance sustainability in PEDs. The sensors acquire information (i.e., occupancy, carbon footprint and thermophysical parameters) which are reworked to monitor indoor air quality, energy balance, costs, etc.

However, it is highlighted that specific business models tailored for the optimization of PEDs using digital twins are missing. Despite this, within the literature experiences, advanced energy management strategies are taken into consideration only in [106,157] through MCA and in [155], where metrics are used.

More in detail, in [106], a scenario based on energy cooperation and the use of a P2P platform in which citizens participate is studied. This case is compared with another scenario based on the creation of a virtual network of digitally connected prosumers in the hypothesis of flexible prices. The results show that the first scenario has a better sustainability score and greater stakeholder preferences.

In [157], the strategies include: the optimization of energy flows through the charging of electric vehicles using the vehicle-to-grid (V2G) and grid-to-vehicle (G2V) schemes; the implementation of ventilated walls and the smart control of artificial lighting. Moreover, in [155], a V2G station is included in the energy plant powered by hydrogen obtained through an electrolyzer fed by the PV system. Overall, the system generates a decrease in CO_2 compared to the base case of 62%.

In the context of energy systems, Guarino et al. [137] also compared two energy scenarios for a solar community from the life cycle point of view. It is found that the inclusion of a solar system with storage, coupled to a district heating network and a seasonal storage, guarantees better performance for all indicators. For instance, ozone depletion is reduced by approximately 78%, while land use is reduced by 27% compared to the base case.

There are several experiences of sharing economy through business models also optimizing the exploitation of solar energy. As an example, in mySMARTLife, a model foresees the possibility for small energy consumers (e.g., renters of apartments) to rent a PV panel from a larger plant. Solar production is automatically calculated in the energy bill once the rental contract is activated [190].

Besides the circular economy models, Living Labs could also contribute to the eco-sustainable design of PEDs and ensure long-term environmental benefits. Specifically, these laboratories could represent an open eco-innovation body and dialogue between citizens, governors, researchers and all other stakeholders also in PEDs [191]. In this regard, there has been a growing interest in the experimentation of Living Labs [157,192,193]. For example, Engez et al. [194] explore the potential of living labs as ecosystems specifically aimed at improving the environmental sustainability of an urban district and strengthening the circular economy. The case study is equipped with a biochar production plant, a vertical farming system and dry toilets. As discussed, the collaboration and co-creation between entrepreneurship, research and inhabitants, typical of these laboratories, contributes to the environmental sustainability of the urban area and optimizes the use of resources and economic value in circular economy models. In the same direction, Bracco et al. [157] implement the Living Lab approach aimed at integrating ICT and smart technologies into the urban environment in an environmentally and socially sustainable way in order to design a sustainable and smart district. Findings show that the living lab approach contributes to achieving a better ecological footprint, raises people's awareness and favors the co-participation of all stakeholders.

On the other hand, in [195], the potential of mobile apps aimed at directing citizens' awareness towards eco-sustainable actions is highlighted, also in relation to the possible reduction in the carbon footprint in Positive Energy Districts. The Living Lab concept is further developed in [106]. Specifically, authors have developed an MCA optimized in the involvement, interaction and empowerment of users and in co-participation along the district planning process, the Multi-Actor Multi Criteria Analysis (MCMCA).

3.2.1. In-Depth Analysis of LCA Methods

This section reports an in-depth analysis of the literature studies focused on LCA for the sustainable design of innovative districts. Experiences are categorized in Table 5 according to the main boundary conditions of the analysis.

As can be seen, there is a high asymmetry between the studies in relation to the assessment of the impacts. Most of the studies focus only on climate change mitigation and use GHG emissions as the indicator of the study.

In addition to greenhouse gas emissions, other important impact categories should be included in the study both in relation to other environmental impacts (pollution, ozone reduction, eutrophication, etc.) and to social effects (human toxicity, cancer effects). To overcome this, the LCA results could be interpreted by analyzing multiple impact categories or calculating the total life cycle environmental footprint, as in [52,56]. This indicator considers a wide range of impacts (GHG emissions, ozone, acidification, eutrophication, land use, freshwater ecotoxicity, use of water and fossils, mineral and metal resources, human health and toxicity) appropriately weighted by weighting factors that take into account regional differences in terms of data priority and robustness.

Another asymmetry is traced in the elements of the urban district included in the analysis. Buildings are subject to LCA assessment in all experiences, with the exception of [134,137,148,150,151], whose objective is the comparison of energy scenarios from a life-cycle perspective. Urban transport is included in the analysis in about 45% of cases, while energy systems for 72%. Less common is the LCA study of energy infrastructures (18%) and the design of open spaces (18%).

Despite the potential of the agri-food chain and local food production in improving the environmental sustainability of the urban fabric, within the sustainable urban district, it is limited and the LCA of the food chain is presented only in a paper. Expanding research on the topic also contributes to the implementation of a circular urban vision. From this perspective, the LCA could facilitate the transition towards a circular economy, supporting the eco-design of products and systems and the assessment of the real benefits related to circular business models. This reasoning also applies to the construction sector as LCA studies have found that embodied emissions are a relevant share of the total GHG emissions and highlight the importance of use materials with low embodied emissions. As an example, Lausselet et al. [133] found that embodied emissions are 56% of the total, mainly due to the mobility sector, dominating the operating emissions that account for 44%.

In [143], it is highlighted that the mobility operation impact consists of 44% of the total GHG emissions, while it is 17% for transport-embodied emissions. On the other hand, embodied emissions in building materials account for 17%.

In this context, recent research developments [186] have demonstrated the effectiveness of LCA in identifying priority urban interventions for the mitigation of environmental impact through the mapping of embedded GHG emissions. The quantification of embodied emissions in innovative urban districts is further studied in [142]. Specifically, Lausselet et al. define and test in a ZEN a simulation and quantification model of the material flows and embodied emissions over time due to construction, renovation and demolition activities. The model combines the LCA with a dynamic method of Material Flow Analysis (MFA), taking into account the long-term temporal aspects that influence the LCA study. The method is divided into the following phases:

- Development of detailed inventories of building materials.
- Simulation over a broad time horizon of the evolution of the building stock in relation to construction, renovation and demolition works. The analytical model, implemented in MATLAB, calculates the annual building stock as that of the previous year to the one considered plus any new constructions and less demolitions during the year.
- Data input in Python environment and calculation of material flows.

The results show that 52% of the embodied emissions are due to the construction phase and 48% to the refurbishment.

Table 5. Focus on relevant experiences of LCA application at district scale.

References		Computational Details		Systems Boundaries			
Authors.	**Ref.**	**Functional Unit**	**Indicators**	**Analysis Elements**	**Production**	**Use**	**End-of-Life**
ATELIER	[55]	(n/s)	GHG emissions, life cycle non-renewable primary, energy demand, life cycle environmental footprint	Buildings	√	√	√
				Transport	√	√	√
				On-site energy systems	√	√	√
SmartEnCity	[75,196]	1 m²/y per building type	GHG emissions, life cycle environmental footprint, cumulative primary energy demand (use of renewable and non-renewable primary energy resources used as raw material and use of renewable primary energy excluding energy resources used as raw material), hazardous and non-hazardous wastes disposed, exported energy	Buildings	√	√	√
Lausselet et al.	[133]	(n/s)	GHG emissions	Buildings	√	√	(-)
				Transport	√	√	(-)
				Open spaces	√	√	(-)
				On-site energy systems	√	√	(-)
				Energy networks	√	(-)	(-)
Lausselet et al.	[128]	"to build and refurbish 20 single-family houses of passive standards (constituting the neighborhood) over a 60 years period, deliver energy for heating and electric appliances and provide mobility by passengers cars for all the inhabitants"	GHG emissions	Buildings	√	√	(-)
				Transport	√	√	(-)
				Energy systems	√	√	(-)
Walker et al.	[134]	(n/s)	Life cycle energy performance	Energy systems	√	√	√
Cerón-Palma et al.	[135]	(n/s)	GHG emissions, life cycle energy demand	Buildings	(n/s)	√	(n/s)
				Energy systems	(n/s)	√	(n/s)
				Green spaces	√	√	(n/s)
				Food	√	√	(n/s)
Nematchoua et al.	[136,138]	(n/s), Two functional units: one per occupant and	GHG emissions, acidification potential, energy consumption, water consumption, waste	Buildings	√	√	√
		one per m²	production, abiotic ozone depletion, eutrophication potential, ozone depletion potential,	Energy systems	√	√	√

			radioactive waste production, damage to biodiversity, damage to health, odors	Open spaces	√	√	√
				Green spaces	√	√	√
Guarino et al.	[137]	"to satisfy the heating and cooling requirements of the district"	GHG emissions, ozone depletion, human toxicity, non-cancer effects, cancer effects, particulate matter, ionizing radiation, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, land use, mineral–fossil resource depletion	Energy systems	√	√	(-)
Lausselet et al.	[142]	"to fulfill the housing demand in terms of residential buildings for the 2500 inhabitants of Ydalir, including a school and a kindergarten, for a timeframe of 60 years starting in 2019"	GHG emissions	Buildings	√	√	√
Lausselet et al.	[143]	"to fulfill the housing, school, kindergarten and mobility needs of the 2500 inhabitants of Ydalir over a 60 year time period"	GHG emissions	Buildings	√	√	(-)
				Transport	√	√	(-)
				Infrastructure	√	√	(-)
				Networks	√	√	(-)
				On-site energy systems	√	√	(-)
Lotteau et al.	[145]	(n/s)	GHG emissions, primary energy consumption	Buildings	√	√	(-)
				Open spaces (green spaces, roads, parking)	√	√	(-)
				Transport	√	√	(-)
Nematchoua et al.,	[139]	(n/s)	GHG emissions, life cycle energy demand	Buildings	(n/s)	√	(n/s)
				Transport	(n/s)	√	(n/s)
				Energy systems	(n/s)	√	(n/s)
Nematchoua et al.	[140]	"Residential eco-district of 3.5 ha comprising 1 ha of roads, driveways and parking lots, 17800 m² of the green space, 19740 m² of the floor space, housing around 220 people, studied on a life cycle of 80 years and located in Liege in Belgium"	GHG emissions, acidification potential, energy consumption, water consumption, waste production, abiotic ozone depletion, eutrophication potential, ozone depletion potential, radioactive waste production, damage to biodiversity, damage to health, odors	Buildings	√	√	√
Nematchoua et al.	[141]	"One square meter per living area"	GHG emissions, acidification potential, energy consumption, water consumption, waste	Buildings	√	√	(n/s)

			production, abiotic ozone depletion, eutrophication potential, ozone depletion potential, radioactive waste production, damage to biodiversity, damage to health, odors	Transport	(n/s)	√	(n/s)
				On-site energy systems	√	√	(n/s)
Palumbo et al.	[146]	"8910 m^2 of open area, about 190 housing units with 10879 m^2 of living spaces and 475 inhabitants"	GHG emissions	Buildings	√	√	(-)
				Open spaces (heat island effect)	√	√	(-)
				Waste	√	√	(-)
Hafner et al.	[147]	"One square meter of the gross floor area"	GHG emissions, primary energy consumption	Buildings	√	√	√
Rossi et al.	[148]	1 kWh of energy generated	GHG emissions	Energy systems	√	√	√
Bakhtavar et al.	[150]	(n/s)	GHG emissions, human health impact, eco-system damage, resource depletion	Energy systems	√	√	√
Karunathilake et al.	[151]	1 MWh of energy generated	GHG emissions, ionizing radiation, ozone depletion, human toxicity, particulate matter, ionizing radiation, photochemical oxidant formation, acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity, urban land occupation, natural land transformation, water–mineral–fossil resource depletion	Energy systems	√	√	√

✓, included in the analysis and explained with details in the paper; (n/s), not specified in the paper; (-), not included in the analysis.

If the system boundaries are concerned, the entire life cycle of the elements included in the analysis is assumed in about 53% of cases. In most of the applications, the evaluation of the end of life is neglected. Furthermore, the interpretability and the comparison of the studies and the benchmark of results are difficult to carry out due to the lack of information on the methodological assumptions (cut-offs and simplifications) and boundary conditions: functional unit, system boundaries (Table 5).

In this context, Lausselet et al. [128] suggest the use of a functional unit "per neighborhood" and another "per person", while the unit of living area of the neighborhood is not recommended because it could provide misleading results.

However, the authors highlight that LCA studies on such a large and complex scale could be affected by high uncertainty due to the lack of data, which led to the use of multiple databases in this study. This uncertainty is also addressed in [134], by means of Monte Carlo probabilistic sensitivity analysis, but in the overall framework of LCA analysis, this issue is not properly contained.

In addition, as discussed in [128], the decarbonization rate of the electricity mix, which is bound to vary over time, influences the results and causes further uncertainty as well as the climatic variations due to global warming. Despite that Nematchoua et al. [136] conducted a dynamic LCA taking into consideration the effect of climate change, in most of the studies the issue is not addressed.

On the other hand, sensitivity and dominance analyses should be largely used as tools to fully grasp the complexity behind aggregated LCA data.

As an example, Guarino et al. [137] have carried out a dominance analysis aimed at investigating the contribution of all the energy system components to each impact category. As result, energy storage devices are mainly responsible for land use and the impact on human health, while heat pumps significantly affect GWP. This degree of detail makes it possible to outline future research directions aimed at improving the life cycle impact of such systems and guide stakeholders in planning priority interventions.

4. Discussion

This section reports the discussion of the results of the review on the design and evaluation approaches of environmental sustainability of innovative districts aimed at PED status or with similar sustainability objectives.

From the overall framework, the identification of holistic and systematic approaches for the transition to eco-sustainable and circular districts is needed. Although some experiences are available of regeneration of urban districts inspired by the principles of circular economy and eco-design, they are mainly based on autonomous sectoral policies and, to date, there is still no overall strategic vision. As discussed in [191], this leads to "thematic silos" between actions due to the lack interconnections. As a consequence, fragmentation in planning results in level sub-optimizations and a non-optimized overall framework which could compromise effectiveness in sustainability.

On the other hand, the multifaceted nature of the sustainable design of PEDs requires further complements of analysis. To avoid "disciplinary silos" between technical and social aspects in the conceptualization of the PED [191], the environmental sustainability of PEDs should be thorough within the overall design framework, simultaneously taking into account the trend of socio-economic co-impacts. The design framework should consider the close connections between material flows, resources and occupants that characterize the PED, as it can be assimilated to the concept of a complex system [95]. Compared to the experiences discussed in the paper, future works should further deepen this complexity through an analysis of interconnections based on parallel and not successive steps. Along this line, the general methodological approach should imply the joint application of techniques and indicators, according to a holistic thinking, and not their mere juxtaposition.

In this context, there is a need for integrated sustainability approaches and for thematic and sectoral synergies for PEDs.

In this regard, and based on the reviewed scientific experiences, the integration of LCA with other KPI-based approaches according to a single holistic vision could be helpful in bridging this research gap, although it is limited.

On the one hand, adopting a life cycle perspective is essential for PEDs to be fully eco-sustainable, and on the other hand, using appropriate KPIs could, in fact, also address issues that have remained in the shadows, related to:

- Socio-economic aspects, i.e., human health and well-being, citizens and stakeholder involvement and empowerment;
- Environmental co-impacts, i.e., green gentrification, creations of green jobs;
- Additional environmental sustainability actions, such as circular economy strategies and business models, also considering that the circular vision requires significant changes at the industrial and city level as the economic chain must rearrange itself on new production balances, while citizenship should shape its behavior in relation to the management of resources and waste.

Furthermore, it is noted that the methodological approach of sustainability assessment should be more adopted in the early design stage of sustainable districts. This view would entail a higher sustainability potential and a more effective use of trade-off analysis between the design scenarios of the PEDs.

Along this line, the early phase of the design process could be even more effective by focusing on addressing other research gaps:

- The evolution of the long-term impacts should be monitored through dynamic analyses, still little used;
- The expected effectiveness of the planned sustainability actions with respect to the achievement of the SDGs should be studied in detail;
- The boundaries of the system subject to the sustainability assessment (buildings, energy systems, infrastructures, food, mobility, public lighting, etc.) should be standardized in order to harmonize the approaches and make the results comparable.

Finally, in most of the districts studied, the Demand Side Management (DSM) approaches, which are important for balancing the energy flows within the PED, are not applied. In this regard, it would be interesting to test sustainability approaches also in areas in which flexible energy management schemes (i.e., through Rule-Based Control and Model Predictive Control) are implemented. Furthermore, flexible energy control can contribute to the sustainability of buildings [197–203]. Although the focus has been based on the single-building scale, interest from the scientific community and the IEA towards the concept of energy flexible clusters is on the rise [203–205]. In conjunction with this, as discussed in the introductory section, energy flexibility could be one of the requirements for achieving PED status. Therefore, the need to integrate the knowledge and skills on environmental sustainability of PEDs with those related to advanced energy modeling is emphasized in order to study their impacts.

The section further continues in two sub-paragraphs focused on the specific macro-topic addressed while maintaining reciprocal links.

4.1. Life Cycle Thinking Applications

The application of LCT in innovative and sustainable districts, such as PEDs and ZENs, is characterized by high complexity. This is induced both by the technological and logistical heterogeneity and innovation required and by the scale of the study. The district scale requires the analysis of various elements such as buildings, infrastructures, energy systems, mobility, open spaces, local food production and other services.

The life cycle perspective applied to innovative urban districts aimed at the PED/ZEN status highlights apparently hidden impacts, not manifest during the use phase, which however cannot be ignored if the project is to be truly eco-sustainable and resilient. In this regard, the results of the LCA highlight the need for improvements in the eco-profile of transport materials and components, to which a considerable share of embodied emissions is associated and, secondarily, also air conditioning systems and DHW production due to the high incidence on the environmental impact of buildings.

Based on the comparison and analysis of the results of the LCA-based applications, some points for discussion clearly arise in terms of research needs and critical elements:

- The need for greater transparency in the dissemination of LCA studies and for the definition of harmonization approaches for the application of the methodology in the complex field of sustainable urban districts. On the other hand, a modeling harmonization is required in order to standardize the system boundaries, the time period, the functional unit, the assumptions, the cut-off rules to be selected in the LCA study of a PED. This point is essential for LCA to be widely used in sustainable districts from an eco-design perspective, ensuring comparability between studies.
- A hot-spot that requires further research progress is the modeling of the end-of-life of the PED elements included in the analysis; in particular, of innovative technologies and infrastructures and systems for flexible control. Indeed, due to the lack of uncertainty of data, the results show that in most cases, the final phase of the life cycle is not studied.
- The need for reliability, achievable through a wider use of sensitivity and dominance analysis. These analyses allow the identification of significant impact factors, in accordance with the completeness, sensitivity and consistency checks to which the LCA study should be subjected and facilitate the choices of stakeholders in planning priority interventions.
- Although there are examples of LCA modeling under different scenarios of progress in the decarbonization of the economy and climate change, in most cases, the study is not iterated for different future scenarios, and the resulting uncertainty (variation in energy consumption for the air conditioning of buildings, variations in the carbon intensity of the regional and national energy mix that will also induce changes in the eco-profiles of industrial products) is not adequately addressed. In this context, there is also a need for modeling tools for these robust and reliable future predictions which should be integrated with the LCA. In addition, due to the long life of buildings and infrastructures, further uncertainty relates to the allocation of impacts over time, to technological progress, to the efficiency and modernization of industrial protocols and production chains which will certainly take place in the long-time horizon. Thus, approaches of dynamic LCA could lead to a greater reliability of the results and to the reduction in uncertainty related to the long-term developments of materials and technologies.
- Although there is growing interest in the LCA of the agri-food chain, the scientific literature including the study of local food production in green areas, within the sustainable urban district, is limited. Inter alia, at the district scale, the circularity actions in districts mainly concerned the electrification of mobility combined with the use of RES for the production of electricity, the use of second-life energy storage batteries and the industrial symbiosis for heat recovery. Food is one of the strategic sectors for the development of a circular pattern of production and consumption, as also underlined by the establishment of the “Circular Economy for Food” [206]. Despite this, only in a few cases and not in PEDs, the food chain is the object of research and experimentation of innovative circularity strategies. This is a research gap towards which future research should be oriented, since it would contribute to the achievement of the objectives set out in the SDG Agenda on the one hand and to the creation of a healthy, stimulating and mixed-use urban fabric on the other.

4.2. Key Performance Indicators

About the KPIs used, the following remarks can be formulated:

- In most of the LCA applications, only the "*climate change*" impact category is assessed. However, for a more complete assessment, it is recommended to include other impact categories related to other environmental issues (such as pollution, eutrophication, land use, ozone depletion, etc.) as well as categories that take into account the impact on human health in order to avoid moving impacts from one impact category to another or neglecting potentially significant impacts.
- With regards to circularity, specific indicators for quantifying the percentage of reuse of products and energy recovered from waste should be included in the whole KPI set. In this regard, some useful examples are as follows:
    1. Percentage of electrical and thermal energy produced from wastewater treatment (ISO 37122: 2019);
    2. Solid waste, other liquid waste treatment and other waste heat resources as a share of the energy mix per year (ISO 37122: 2019);
    3. Electrical and thermal energy produced from solid waste or other liquid waste treatment per capita per year (ISO 37122: 2019);
    4. Percentage of biosolids that are reused (dry matter mass) (ISO 37122: 2019);
    5. Energy derived from wastewater as a percentage of total energy consumption (ISO 37122: 2019);
    6. Reduction in water consumption through the management of black, gray and rain water (Medved [153]);
    7. Per capita waste production (Medved [153]);
    8. Percentage of biogas from compost and vacuum toilets (Medved [153]).

Furthermore, indicators more specifically designed for the analysis of circular processes are necessary. Greater attention is required regarding the eco-design of products, which is not sufficiently investigated as part of the revised sustainable district projects. Parameters such as embodied emissions in building materials and technologies and the use of eco-friendly materials should be assessed and quantified. Examples of KPIs that could fill this gap are:

1. Reduction in embodied energy of products and services used in the project (CITYkeys);
2. Share of recycled input materials (CITYkeys);
3. Share of renewable materials (CITYkeys),
4. Share of materials recyclable (CITYkeys);
5. Lifetime extension (CITYkeys);
6. Material footprint (SDG Agenda);
7. Domestic material consumption (SDG Agenda);
8. Use of ecological building materials (Medved [153]);
9. Percentage of buildings with passive energy measures and built with recycled materials (Medved [153]).

- The overall environmental framework could be further integrated to take into account other environmental aspects. In this context and as highlighted in the Sustainable Development Agenda, the environmental impact mitigation plan of urban districts should also include models of integration between the natural landscape and the built environment; protection of natural habitats and rare species of plants and animals; and, as discussed within CITYkeys, the conservation of cultural heritage. In addition, given the correlations with energy consumption in buildings, climate change, human health and productivity [207–210] and the growing interest in air quality monitoring [211], more attention should be paid to indoor and outdoor air quality in sustainable districts. In this regard, targeted ventilation measures, air quality control and specific KPIs, such as the no. of real-time remote air quality monitoring stations per square kilometer and percentage of public buildings equipped for monitoring indoor air quality (ISO 37122: 2019), could be helpful.

- An important environmental issue not sufficiently mentioned within the scientific literature and the revised EU pilot projects is that relating to the phenomenon of heat islands. As heat islands worsen urban environmental performance and also impact social well-being, recent research is focusing on urban cooling strategies based on appropriate material albedo coefficients and green infrastructure [16,212,213]. Along this line, the innovative design of urban settlements should take this issue into consideration and include tailor-made actions to stem it. In this context, the KPI: urban heat island-maximum difference in air temperature within the city compared to the countryside during the summer months (CITYkeys) and specific modeling tools could be useful.
- Finally, specific KPIs related to sustainable food should complement the overall set of indicators. Some examples are:
    1. Annual total collected municipal food waste sent to a processing facility for composting per capita (ISO 37122:2019);
    2. Global food loss index (SDG Agenda);
    3. Proportion of agricultural area under productive and sustainable agriculture (SDG Agenda);
    4. Local food production (CITYkeys);
    5. Self-sufficiency food (CITYkeys);
    6. Increase in the share of local food production due to the project (CITYkeys).

Other KPIs should take into account the potential for local food production in terms of the number of green spaces that can be used as vegetable gardens, green roofs, etc., the effects on the community in terms of jobs created and inclusion of citizens and synergies with local farmers. Furthermore, the environmental benefits should be assessed not only in terms of emissions and energy demand reduction, as in the reviewed studies, but also in terms of waste production and water consumption reduction by treating building wastewater or rainwater.

5. Conclusions and Future Outlooks

During the last few years, increasing attention has been paid to the new emerging concept of PED by the scientific community through specific directives, policies and initiatives aiming to spread the PED paradigm in European cities.

In this context, this literature review has a specific focus on environmental sustainability within innovative and eco-sustainable districts such as PEDs, ZENs, NZEDs and other sustainable urban agglomerations. The results of the literature review show that some relevant areas of environmental sustainability could receive further attention, such as sustainable food and the overall circularity, the mitigation of urban heat islands and some co-impacts, such as green gentrification, and targeted and tailored strategies for PEDs should be designed.

Specific shared economy and circular economy models for PEDs, which summarize the plurality of stakeholders involved and aim to create synergies to cogenerate value, developed in a single, non-fragmented optimization framework, are needed. For the models to be effective, holistic thinking is required in order to adequately take into account the synergies between sectors, industrial and residential symbiosis and the interchanges of resources, materials and energy. In this regard, some incentives for high environmentally performing products could facilitate the transition towards the green economy.

As for the methodological point of view, a higher degree of harmonization between sustainability approaches is essential for a homogenous and comparable framework, which favors the exchange of know-how between projects and the comparability of results. In this context, LCA could play a pivotal role with regards to the organization of a harmonized framework with regards to system boundaries, impact categories and assessment methodologies. Therefore, there is a need for coordination between LCA analysts and political decision-makers aimed at maturing synergistic industrial policies and practices with the sustainable urbanization plans of the PEDs and more generally of the cities of the future.

New research trends on sustainable districts aim at the integration between LCT techniques and KPI-based evaluation approaches in order to obtain comprehensive design environments. From this perspective, some challenges should be addressed in the development of LCA studies, such as long-term uncertainty due to climate change, data availability and the energy decarbonization, through dynamic models.

In addition, there is a need for a greater use of sensitivity and dominance analyses to explore the effects induced on the impact categories examined by the design strategies and take into account the synergies between the three dimensions of sustainability for the PED to be sustainable. The framework of sustainability KPIs could use the integration of some dedicated KPIs, among those defined in the Sustainable Development Agenda, the main European standards and initiatives and the relevant literature experiences.

Furthermore, future outlooks should be directed towards:

- The harmonization of assessment methodologies in the peds with reference to modeling assumptions and methodological choices in order to guarantee comparable results;
- The development of dynamic environmental analyses taking into account long-term uncertainties and energy flexible control;
- The enrichment of the existing PED framework including SDG-based indicators, integrated KPIs referring to also economics and social sustainability and integrated evaluation approaches;
- The analysis of the expected effectiveness of the planned sustainability actions with respect to the achievement of the SDGs;
- The analysis of sustainability of peds in the early design stage through an extensive use of trade-off analysis between design scenarios.

According to this vision, the Positive Energy Districts, in addition to being hubs of energy innovation, can also be a bulwark of the concept of sustainable development in its most faithful and complete meaning defined by the SDG agenda, guaranteeing the socio-economic well-being of the inhabitants and the mitigation of all anthropogenic environmental impacts.

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Abbreviations

Nomenclature

Abbreviations	
BESS	Battery Energy Storage Systems
DHW	Domestic Hot Water
DSM	Demand-Side Management
CBA	Cost Benefit Analysis
CHP	Combined Heat and Power
EU	European Union
EU H2020	European Union Horizon 2020
EV	Electric Vehicles
G2V	Grid-to-Vehicle
ICT	Information and Vommunications Technology
IEA	International Energy Agency
JPI	Joint Programming Initiative
KPI	Key Performance Indicator
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MFA	Material Flow Analysis
MPC	Model Predictive Control
NZED	Net Zero Energy District
PCM	Phase Change Materials
PED	Positive Energy District
PEB	Positive Energy Building
PEN	Positive Energy Neighbourhood
PV	Photovoltaic System
RBC	Rule-Based Control
RCP	Representative Concentration Pathways
REC	Renewable Energy Community
RES	Renewable Energy Sources
SDG	Sustainable Development Goal
SET	Strategic Energy Technology
SD	Sustainable District
SH	Space Heating
S-LCA	Social-Life Cycle Assessment
SPEN	Sustainable Plus Energy Neighborhood
TES	Thermal Energy Storage
UM	Urban Metabolism
UN	United Nations
V2G	Vehicle-to-Grid
ZEB	Net Zero Energy Building
ZEN	Zero Emission Neighborhood
Indices	
nren	Non-Renewable Primary Energy

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