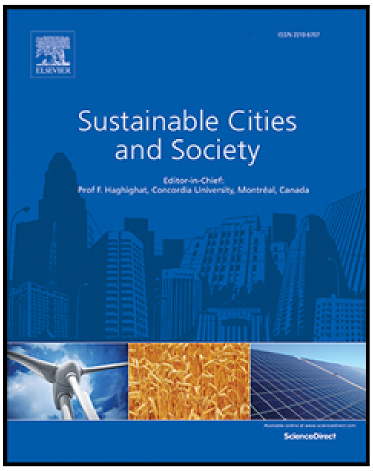

‘Decarbonizing Europe’ A Critical Review on Positive Energy Districts Approaches

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‘DECARBONIZING EUROPE’
A CRITICAL REVIEW ON POSITIVE ENERGY DISTRICTS APPROACHES

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HIGHLIGHTS

- Positive Energy Districts are gaining importance as climate-neutral living strategies.
- PEDs arose from (net) zero energy buildings to meet the energy balance.
- This work is a critical angle on PED reviews unveiling the gaps in human-centric solutions.

Abstract

Positive Energy Districts (PEDs) are gaining importance as urban innovation labs and promising climate-neutral living strategies. The concept aims to accelerate the decarbonization processes and scale up the ecological transition; nonetheless, multiple challenges are emerging due to the complexity of the urban systems. This work provides a critical angle on the existing methods, tools and approaches for PEDs' conception and operation unveiling the multiple gaps in human-centric solutions, and concrete regulatory framework among others. The booklets on PEDs realized grant the importance of citizen empowerment and stakeholders' synergies to generate pragmatic and long-term contexts to facilitate their deployment. The study significantly contributes to the literature by leveraging the importance of knowledge gaps and recognizing the systemic nature of the urban scale. Together, the review serves to provide a comprehensive analysis and an in-depth vision of what lenses PED design and conceptualization and supports the holistic and human-oriented visions to prioritize the users' role for livable, sustained and autonomous communities.

Keywords: Decarbonization; Positive Energy Districts; Energy Transition; Methods

1 INTRODUCTION

1.1 Background and Motivation

In a continuously globalized world, cities, as communication hubs, are responsible for more than two-thirds of the world's energy and are the main originators of climate change averting the worst effects of the (possibly) greatest humankind challenge [1]. At the same time, Europe's bets around the global energy transition reveal the cities' decisive role in the comprehensive approaches towards sustainable urbanization including spatial, social and economic perspectives.

In this sense, an important milestone in the European Union (EU) in the path toward tackling Climate Change was in 2007 has been the "2020 Climate and Energy Package" [2], and the roadmap was updated in October 2014 with the definition of the "2030 Climate & Energy Framework" [3]. Later, in 2018, in line with the EU's commitment to global climate action under the Paris Agreement [4], the European Commission set out the "2050 long-term strategy" for a climate-neutral EU, looking at all the key sectors and exploring pathways for the transition [5], a strategy where the European Green Deal [6] is one of the main flagships.

These main roadmaps and strategies have crystallized during the last decades in a set of regulatory packages and policies that pave the way, providing a legislative framework to enable the European Member States (and then, the European Union as a whole) to reach these objectives. Hence, as far as the building sector is concerned, the Directive 2012/27/EU on Energy Efficiency (EDD) [7] aimed at increasing the energy efficiency for achieving the aforementioned objectives, and highlighted the potential for saving primary energy (PE) of district heating and cooling systems, urging the Member States to carry out a comprehensive assessment of the mentioned potential. Earlier, the recast of the Energy Performance in Buildings

Directive (EPBD) [8], which involved a turning point on the path towards the improvement of the efficiency of the building stock, introduced two key concepts: cost-optimality and nearly Zero Energy Buildings (nZEB).

It should be noted, however, that there is a common agreement that is necessary to scale up to district-level approaches, since they are one of the potentially most effective approaches to speed up the process of reducing GHG emissions in the building sector, allowing also taking advantage of the interactions amongst the different buildings and optimizing the implementation of renewable energy sources. This point is mentioned by the European Union in different Commission recommendations, such as CR-EU 2019/786 of 8 May 2019 on building renovation [9] or the update of the EPBD in 2018, which states that the Commission *"shall review this Directive by 1 January 2026 at the latest"* and *"as part of that review, (…) examine in what manner Member States could apply integrated district or neighborhood approaches in Union building and energy efficiency policy (…) employing overall renovation schemes applying to several buildings in a spatial context instead of a single building"* [10]. Also, the "Renovation Wave Strategy", one of the energy-related actions of the European Green Deal and published by the European Commission in 2020 to double the annual energy renovation rate of buildings, remarked the necessity of developing district and community approaches and integrating renewable solutions for creating zero-energy districts, since *"aggregating projects at this level may lead to zero-energy or even positive energy districts"* [11].

In summary, the main regulatory framework for supporting the PEDs and decarbonizing the building stock.is currently gathered in the "Clean Energy For All Europeans Package [12], which updates the policy framework in line with the EU's Paris Agreement commitments. The package highlights the importance of improving the energy and emission performance in cities as energy hubs have a large potential to limit global warming and reach the Sustainable Development Goals about inclusive, safe and resilient territories, and it addresses four key topics related to districts and communities:

- *Energy Performance in Buildings*. The aforementioned recast of the EPBD [13] paved the way for the reduction in energy demand from buildings across Europe with the first objective of zero-energy for new public infrastructure for 2021 in an attempt to reinforce the performance of the existing building stock. The update of this Directive (EU 2018/844) [14] points out specific measures focused on making buildings more energy efficient.
- *Energy efficiency*. The EED [7] set the foundations for the Energy Efficiency first principle and establishes a common framework to mandate energy efficiency improvements. It aims to enable businesses, the general public and public authorities to manage their consumption. The Directive is also updated [15] to set binding targets related to energy efficiency defined in the previously mentioned 2030 Climate & Energy Framework.
- *Renewable Energy*. The RES Directive was also revised in 2018 (2018/2001/EU) [16] and a proposal for a new revision is currently under evaluation [6]. It requires each MS to adopt its own national renewable energy action plan with sectorial targets and the recast to set definitions for ‘renewable energy communities’ and ‘self-consumers’.
- *Electricity Market Design*. The update of the Internal Market for Electricity Directive [17], which establishes common rules for the internal market in electricity aimed at adapting market rules to increase flexibility for the large-scale integration of renewable energy, has become a major market player.

And other regulatory frameworks, such as:

- The ESR [3] regulates the sectors of the economy that fall outside the scope of the EST – namely transport, buildings, agriculture, non-ETS industry and waste account collectively for almost 60% of total domestic EU emissions, which sets binding national GHG targets for each MS to a 30% cut in emissions by 2030 (2005 baseline).
- The ETS is an EU-wide carbon trading market that fixes a 'cap' on GHG emissions for large installations and provides 'emissions allowances' corresponding to tons of CO_2. Effort-sharing sectors interact with the sectors under the EST and reductions observed by these sectors are linked to the ETS via instruments.

In this context, to accelerate decarbonization and foster the 'scalability' potential, PEDs are being developed as part of 'smart strategies' and hubs for energy-efficient environments [18]. Significant academic work has been performed on the definitions and possible variations (e.g. [19]–[21]); on the development of methodologies for design, energy modelling and simulations (e.g. [10]-[11]) or the outreach of good practices (e.g. [12]-[13]), while the concepts of a 'high energy performance district' has been discussed substantially as a key solution for the energy systems in transition to the carbon neutrality and the long-term purpose of European visions [26].

Overall, PEDs consist of a promising and compelling concept to accelerate decarbonization and urban transitions in Europe, nonetheless, their implementation remains challenging with multiple and fragmented limitations with partially developed analysis focusing predominantly on technological solutions and designs.

1.2 Research Questions and Paper Structure

In the post-COVID era, certain aspects of PEDs design are also being questioned including the densification, the urban forms, the provision of green and public spaces and others relevant to the quality of life and well-being indicators. In this sense, this review seeks the critical dimensions and gaps in the literature of methods on positive and autonomous districts considering the various challenges (urban, social, etc.). Overall, the review serves as an in-depth analytical vision of what lenses PEDs conception and design unveil the importance of holistic and people-centric approaches for sustained and autonomous communities.

The work is structured accordingly (Figure 1). Section 2 overviews the variations of existing methods and tools in line with PED design, key concepts, technologies and others. Section 3 focuses on the particular barriers and challenges of PED operationalization. Section 4 explains beyond the missing points emphasizing the human-centric and people-oriented developments, while Section 5 summarizes the main findings of the review and discusses the future perspectives for further research.

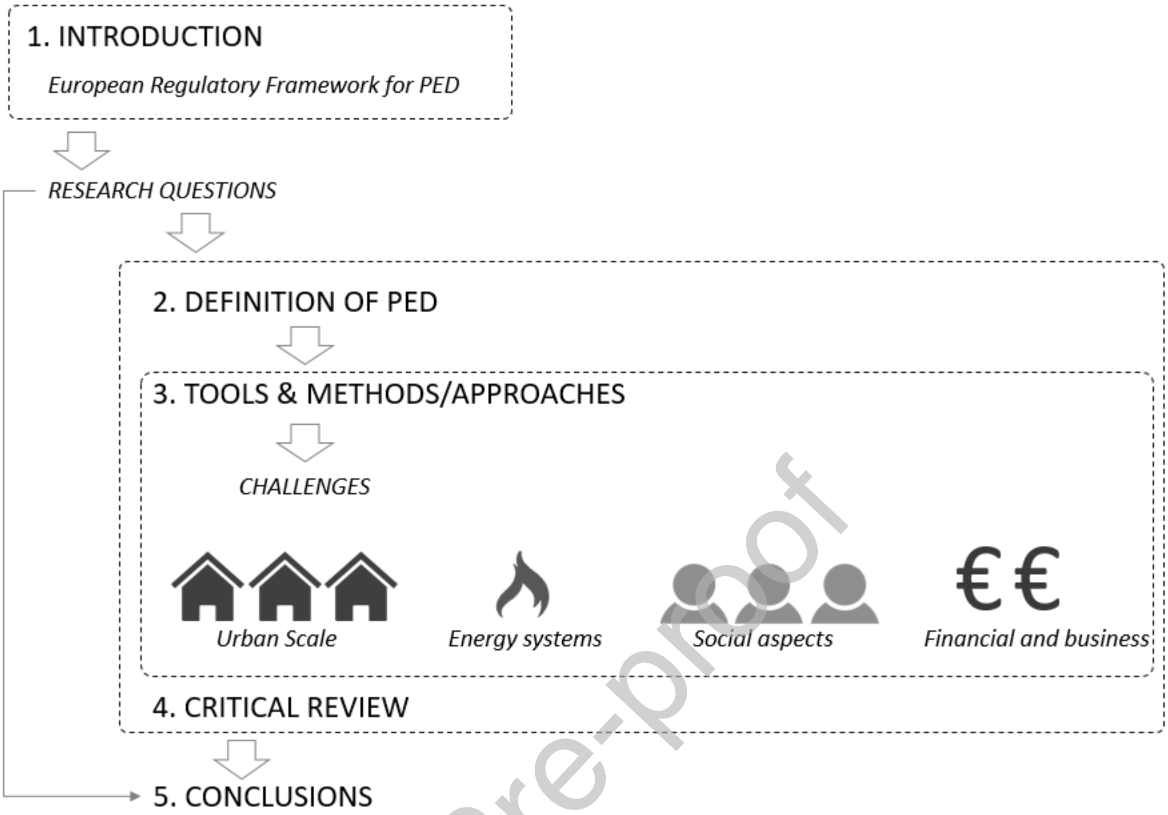


Figure 1. Schematic representation of paper's structure

1.3 Positive Energy Framework. What is a High-Energy Performance District?

PEDs arose from extensively discussed concepts in the literature and terms of *(net) zero energy buildings* (e.g. [21], [23], [27]), *Nearly Zero Energy Buildings* [13], *Energy Positive Neighborhoods* (e.g. [17]-[18]), *Positive Energy Blocks* (e.g. [19]-[20]), *Energy Neutral Districts* [32] under the umbrella of meeting the energy demand from renewable sources. A common thread of these terms is the self-sufficiency and the objective of meeting the energy demands from local energy production despite the diversity in their interpretations. Hence, the topics are related to the geographical boundaries, the interactions with the grid, the methods of the energy supplies and the balancing period (of consumption and production) yearly. **Error! Reference source not found.** overviews the definitions from the literature.

Table 1. Overview of the zero and positive energy concepts from the literature (adapted by [33])

Concept	**Definition**	**Boundaries**	**Interaction with an energy grid**	**Energy supply method**	**Balancing period**	**Sources**
Energy Positive Neighborhood (EPN)	An area that generates more **electricity** than it consumes	Neighborhood	Off-grid	On-site	Annual	[28], [29]
Positive Energy Block (PEB)	A set of **at least three buildings** in close with an average yearly **positive energy balance** (consumption/production)	(Urban) block	On-grid	On/Off site	Annual	[31], [34]
Energy Neutral Districts (END)	**No net import** is required from outside the district	District	On-grid	On/Off site	Annual	[32]
Positive Energy District (PED)	**Energy-efficient, performant and flexible community or urban area with a production of zero GHG emissions and an annual energy surplus derived from the RES local production**	District	On-grid	On/Off site	Annual	[35], [36]

Lindholm et al. [37] defined three types of PEDs characterizing them as ‘autonomous’, ‘dynamic’ or ‘virtual’ depending on the system boundary and the import and export conditions underlining the importance of the urban contexts and impacting factors. Laustsen [38] synthesizes the relevant concepts on the urban scale (Figure 2).

- ***Plus Energy Districts:*** deliver more renewable energy to the grid than they use, producing more renewable energy than they consume.
- ***Net Zero Energy Districts:*** deliver the same amount of energy to the supply grids as they use from the grids, and do not require any fossil fuel for heating, cooling, or lighting.
- ***Zero Stand Alone Districts:*** not connected to the grid and independent in generating their own renewable energy supply with the capacity to store energy in storage systems such as batteries.
- ***Zero Carbon Districts:*** do not use energy from carbon dioxide emitting sources (e.g. biomass, biogas excluded) and over the year will either be carbon neutral or positive energy, therefore they produce enough energy to ensure their energy demand is always at most zero.
- ***Nearly Zero Energy Districts:*** very high-energy performance but do not always reach a zero-energy target over a year, almost all of the remaining energy demand is provided by onsite or nearby renewable energy.

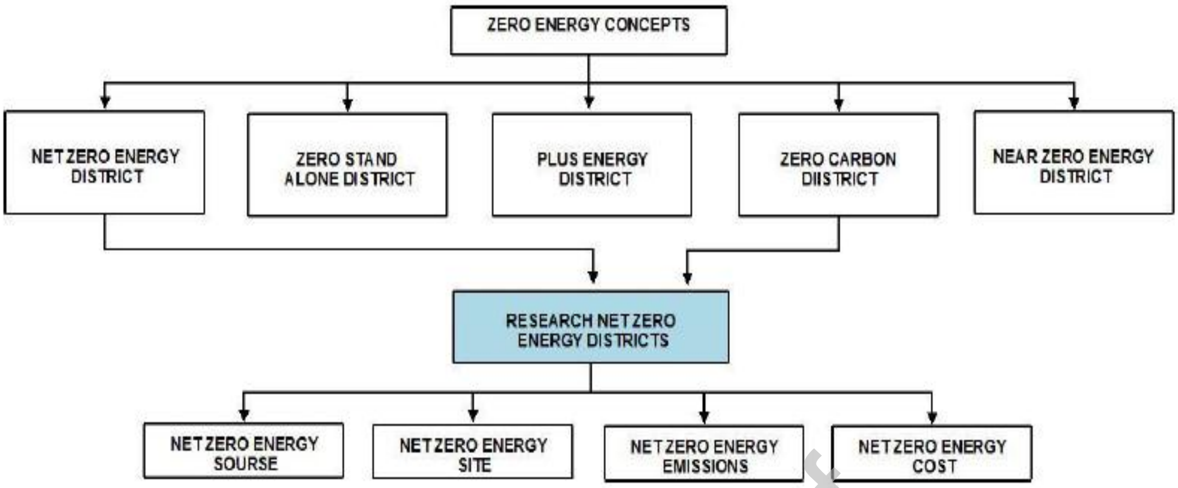


Figure 2. A variety of 'high-energy performance districts' is proposed by Laustsen [38]

In the last years, many empirical and pilot projects about PEDs' implementation across Europe. A major driver for the research on PEDs is the climate and energy policies within the publication of the Set Plan Action 3.2 [36] aiming at the support of PEDs applications by 2025 in Europe and the IEA Annex 83 [39] to address multidisciplinary dimensions to facilitate the development. Yet, the SET (Plan, action 3.2) [36] initiated the PEDs as the *'districts with annual net zero energy imports and carbon emissions'*, a study completed by JPI Urban Europe [40] on the emphasis on the actors' dialogue to optimize their livability. In other words, PED is defined as *'an urban territory with annual zero imports of energy or* CO_2 *emissions aiming to surplus productions of renewable resources'.* In the same study, the implementation ambition for the concept's operationalization is conveyed towards 100 Positive Energy Districts and Neighborhoods in Europe to actively contribute to the resilience of energy systems. An outlook of these operations, as a 2019 compilation, is presented in Figure 3; as of February 2020, there were already more than 20 PED projects at the implementation stage, 32 not declared as a PED but presenting 'interesting potential', while other similar reviews have been published on (nearly/net) concepts at the building (i.e. [41]–[44]) or the district [45] scale but to the best of our knowledge there has not been a systematic review of positive energy/emission/carbon district yet.

Figure 3. Geographical distribution of 100 PEDs in Europe [46]

In reality, most of the PED practical experiences are based on new constructions and planning with limited rehabilitation proposals. Samadzadegan et al. [47] target the heating and cooling demand for the RES systems' dimensions. Moreno [48] calculated the energy balance and performance, while Bambara et al. [49] studied the articulation of the densification and the potential for PED. From a more techno-economic vision, Laitinen et al. [50], analyzing the case of Helsinki, conclude that the PED feasibility is ensured, while projects in the field prove it in practical meaning. Besides the technical aspects, the literature emphasizes the dependency of PEDs by the spatiotemporal factors, including the on-site renewable potential, the storage complexities and the social aspects including the user behavior and adaptation, which are fundamental for integrated approaches to climate-neutral cities.

It remains remarkable that so far, the district level has gained much attention from the scholar community, but with limited outcomes due to its complexity; hence, only a few authors focused on wider areas of energy transition and in particular the PED implementation (e.g. [30]–[32], et al.). A first approach towards the definition is found in Carlisle et al. [51] stating that *'a net-zero energy community has greatly reduced energy requirements through gains efficiency of energy for vehicles; thermal and/or electrical energy within the community is met by RES'*. Jablonska et al. [32] characterized as 'Energy Neutral' a district where no net energy imports are required outside the district's borders (annually) emphasizing the interactions of energy, mobility and ICT in a holistic vision considering ENDs as integral parts of the district energy systems. Broadly speaking, the literature review investigates energy issues at a district scale by focusing on the impacts of urban structure on energy consumption in buildings [52]. In this sense, applying the EPBD (European Commission, 2010) principles in districts, we assume that *'a NZED is a delimited part of a city with high energy performance and a nearly zero or very low amount of energy consumed to a significant extent by its local production and the use of RES on-site'.*

Typically, a district is 'highly performant' when comprises diverse types of energy-efficient buildings and systems and reduces consumption by maximizing the local production by RES with well-understood benefits, some of the most cited are:

- ***Economies of scale***: deriving from on-site renewables, energy storage and other systems, driven down the unit costs of technologies and installations.
- ***Building a load diversity***: lowering the sum of the building peaks and the requirements in heating/cooling.
- ***New business models***: alternative solutions to traditional energy delivery; for instance, building owners or district stakeholders become energy producers.
- ***Grid interactivity***: adjustments of loads to respond to the grid's requirements and enable the utilities and the operations of the network distributions.
- ***Resilience***: reduced downtime and increased business continuity are possible especially if energy storage and microgrids provide uninterrupted power during power outages.

Nevertheless, the planning and PEDs design is a demanding process with a lack of extensive knowledge, practical experiences, data, governance mechanisms, methods and applications and decision-making processes.

2 OVERVIEW OF EXISTING METHODS AND TOOLS

Addressing the city needs, the plethora of the existing methodologies diagnose the city-level indicators to establish a metric point and identify strengths and weaknesses for setting up priorities and action plans. In a macro-form, a key role for peculiar and efficient PEDs is the inclusiveness, co-creation and participatory planning as rules for the energy transition. Hedman et al. [53] using keywords related to the concepts of energy transition carried out a study from 1990 onwards on Scopus database observing the growing interest each year for the issue around its globe, whilst the 'positive' concepts came into the scene since 2018 (Figure 4).

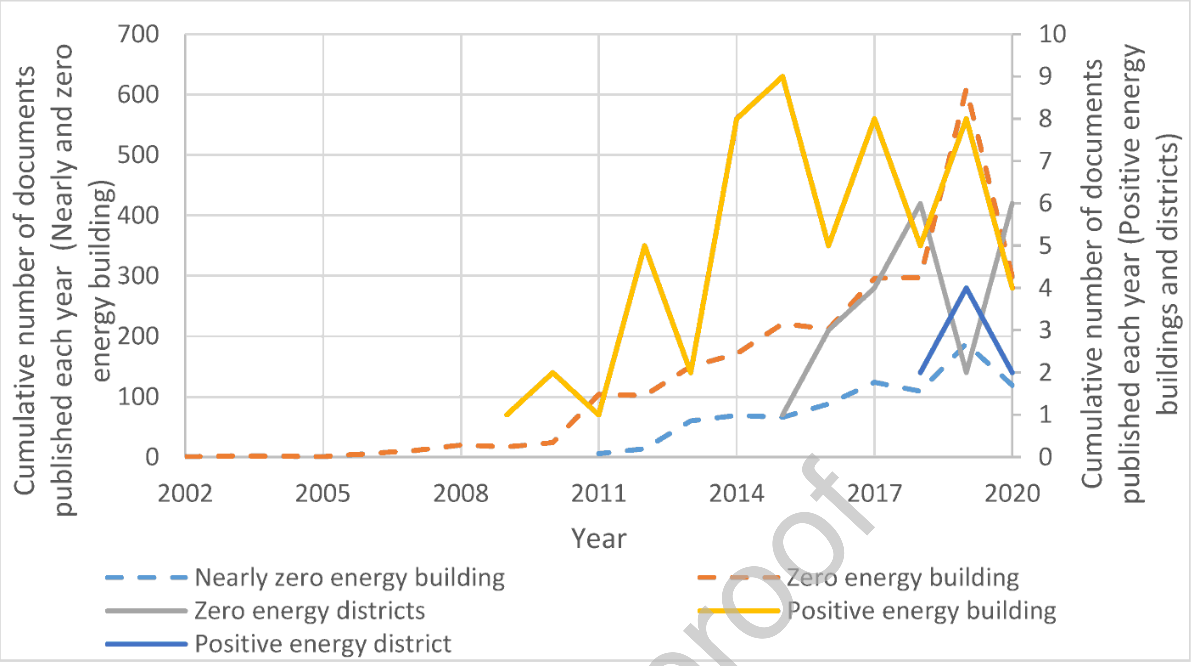


Figure 4. Increase in research interest in energy transition concepts [53]

2.1 Materials and Methods

Literature reveals case studies, tools, methods and projects for developing zero (or positive)-energy (or carbon) districts, which differ from project to project from the calculation of the performance to the cost-optimal solutions. The list of these works is not exhaustive varying from the scale of the individual building to the district level and from metrics of simple indicators to sophisticated and complex methods. The analysis is based on a comprehensive and critical review of PEDs, similar concepts and practical examples already implemented in Europe, classified accordingly (Tables below).

2.1.1 Metrics and Key Indicators on Building Level

As for the KPIs, a wide range of metrics are used including energy-based indexes (e.g. share of renewables, energy mix, consumption, etc.), specific emissions (e.g. greenhouse gases, nitrogen oxide, etc.), circular economy strategies (e.g. recycled waste), water consumption (e.g. grey and rainwater use), mobility (e.g. fuel consumption) among others.

Table 2 includes a checklist on objectives, metrics, design parameters and methodologies on building level from reference frameworks and based on European strategies.

Table 2. Check-list of methods and tools for energy performance on building level

Purpose	Method	Metrics	Key Performance Indicators	Reference(s)
District retrofitting methodologies	✓ Retrofitting approaches ✓ Analysis of the target building ✓ Amount of expected reduced emissions.	(Ton CO2). CO2 (g/kWh). CO2 (g/kWh). GHG (CO2, N2O and CH4) (NOx, Sox)	Buildings: • heating, cooling, ventilation, appliances, cooking, DHW.	A2PBEER 2014 [54]
Cost-optimal energy renovation strategy for buildings	Life Cycle Optimization	Calculation of energy demand	Building envelope: U-values, air change rate, indoor, outdoor temperatures and costs	OPERA-MILP [55]
Energy demand for heating/cooling in building typo-morphology	Dynamic simulations (EnergyPlus)	Total annual energy use (kWh/y)	Buildings' shape, density, site layout	[56]
Impact of design parameters		Total annual electrical energy use (GWh)	Buildings' energy performance level, density, district typology	[57]

2.1.2 Metrics and Key Indicators on Neighborhood/District Level

Earlier studies mostly identified the problem on individual buildings including consistent definitions across the Net/Nearly Zero Energy Building, while recent studies have developed methods to extend the boundaries to neighborhood and district scales. The literature cites frequently the approaches of decision-making problems, such as the LCA, LCC, CBA and other relevant MCDA tools [58]. The Joint Program Initiative Urban Europe has an important role in PEDs' coordination across Europe. Bossi et al. [59] summarized part of PEDs' attributes in geographical aspects, implementation status, land use and building typologies but also the consideration of success factors, limitations and possible barriers, while Brozovsky et al. [60] identified the energy-oriented technologies with approaches related to social and/or climate. Glicker et al. [61] argued for an integrated energy solution both for individual building measures and urban functionalities with novel and smart dimensions focusing on the infrastructures (e.g.

electric vehicle charging, district heating, etc.), integration of active and flexible energy systems and mobility (e.g. VG2) (Figure 5).

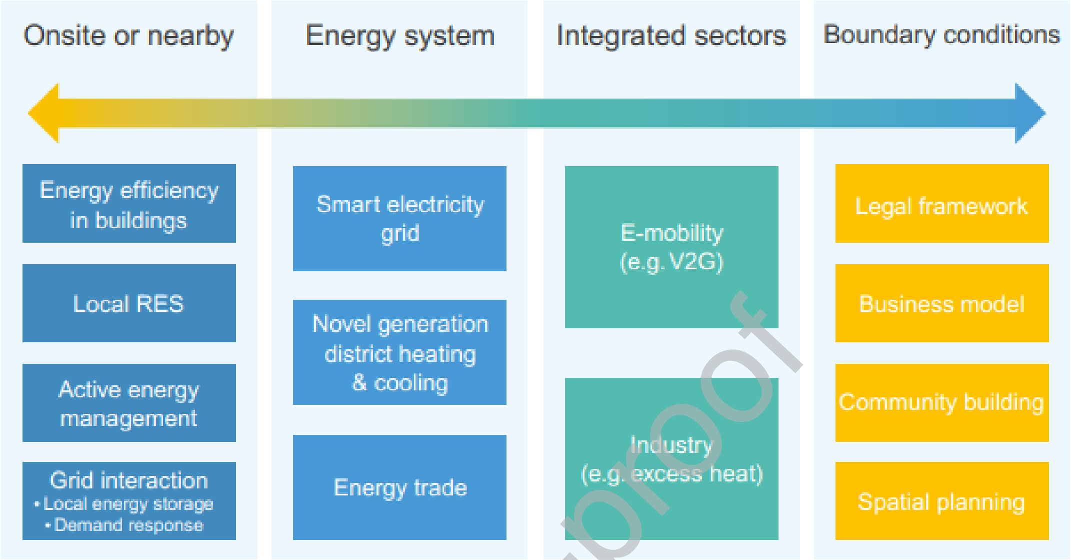


Figure 5. An integrated PEDs' approach [61]

Alpagut et al. [62] discussed a methodology to identify the spatial, physical and technical attributes for energy planning from other similar GIS methodologies as well (e.g. [63]–[66]) and embrace the use of several GIS-MCDA applications to define the critical elements of PED referring to the site selection, the scenario evaluation and the components of the location and propose the synthesis of the spatial information system. The 'bet' for this process remains the harmonization of diverse modes of spatial planning and its nexus to the energy aspects; therefore, this demands an in-depth analysis of the resources potential (offer/on-site supplies), the land-use and energy (master) planning as well as the socio-economic context categorizing this data in 6 types, meaning: the resources' identification and mapping, the macro-scale (urban) typo-morphological analysis, the land-use, the energy infrastructure and services but also the social structures.

Seeking the analysis and adoption of other streams and macro-scale applications, the Life Cycle Assessment encompasses two alternative processes [67]:

- *Operation stage-oriented assessments* [68]*:* with the consideration of large system boundaries and not restricted on buildings but considering other dimensions (i.e. mobility) and other indexes on operational energy consumption-based approaches.
- A broad range of processes and scenarios for the urban environments based on nutrition, mobility and buildings' impacts [69].

On the top of the main research with a more comprehensive dimension are:

- *Multi-criteria methods and optimization* [70] support the decision-making process through mathematical optimization and design variables.
- *GIS methodologies*, as previously cited, regarding the energy modeling of building archetypes based either on top-down or bottom-up views aiming at the integration of renewable energy systems planning.
- *Sustainability certifications:* several available approaches for the PED context with a focus on environmental performance (examples of LEED, BREEAM Communities, etc.).

Table 3. Check-list of methods and tools for energy performance on neighborhood/district level

Purpose	Method	Metrics	Key Performance Indicators	Reference(s)
Highest possible energy saving for districts	✓ Classified the existing residential building stock & developed refurbishment scenarios ✓ Cost-optimal refurbishment solutions based on user-defined scenarios	Minimum energy performance	Energy efficiency measures. District heating/cooling systems and installation of RES technologies	[71]
Assessment of the energy performance of various energy concepts for settlements	Software tool, the District Energy Concept Adviser. Single building energy performance certificates (standard DIN V 18599)	Final and primary energy demand, the CO_2 emissions	Defines district based on archetype buildings with a fixed geometry	Energiekonzept- Berater für Stadtquartiere
Development of a NZED assessment	Dynamic simulations (URBANopt)	kWh (energy for heating/cooling)	Buildings: orientation, envelope attributes, solar potential airtightness, etc.	[72]
Evaluation of energy consumption	Dynamic simulations (ENVI-met)	Electricity use for cooling (kWhp/m2)	Urban layout pattern, street width, street orientation	[73]
Assessment of the urban form on the energy demand	Energy consumption for heating/cooling/ etc. Transportation: Energy consumption for daily mobility	Primary energy for heating (kWhp/m2/y)	Building envelope, transportation	[74]

Towards the PEDs operationalization, Derkenbaeva et al. [33] underline the role of assessment metrics and categorize the methods along with:

I. *The interaction to the energy grid, for* example, the introduction of the **grid interaction index** to represent the energy flows variability annually or the weighting system to uniform metrics for energy balance calculation proposed by Sartori et al. [75].

II. *Energy supplies methods* for the on and off-site energy supplies [76].

III. *Balancing periods* are regularly discussed by scholars. The design of the foremost KPI 'On-site Energy Ratio' by Ala-Juusela et al. [77] is highlighted for the measurement of energy balance between demand and supplies from RES. Other alternatives proposed by Hernandez and Kenny [78] of the incorporation of full building life cycle metrics, e.g. operating energy use, materials, and installations among others.

2.1.3 PEDs and Social Approaches

Nonetheless, research unveils the insufficient consideration of urban energy techniques, while a gap accounts for '**occupant behavior**'. Few cases are observed in the literature including the studies of Soutullo et al. [79] and Fatima et al. [80] with the 'living labs' as drivers for PEDs' replication. Another interesting approach is the discussion by Gouveia et al. [18] related to the historic districts and how the PED model is an opportunity for energy poverty mitigation along with a set of KPIs for the calculation procedures on the energy, environmental, social and economic flexibility.

PEDs and Economic ApproachesOther methods report the cost-efficient achievements of PEDs meeting specific targets of energy efficiency [81] or cost-benefits balances [82], while a particular interest in this framework is featured in the Regulation EU 244/2012 [83] for national economic assessment of energy performance solutions in European buildings. At the same spectrum, macroeconomic methods calculate for instance the employment impacts and society saving or other indicators, e.g. the NPV adopted for typical investment-related indicators [84], the Internal Rate of Return or the Doughnut Economics based on the coherence between economic, environmental and social (e.g. energy justice) interconnections to achieve PEDs (Figure 6) [85].

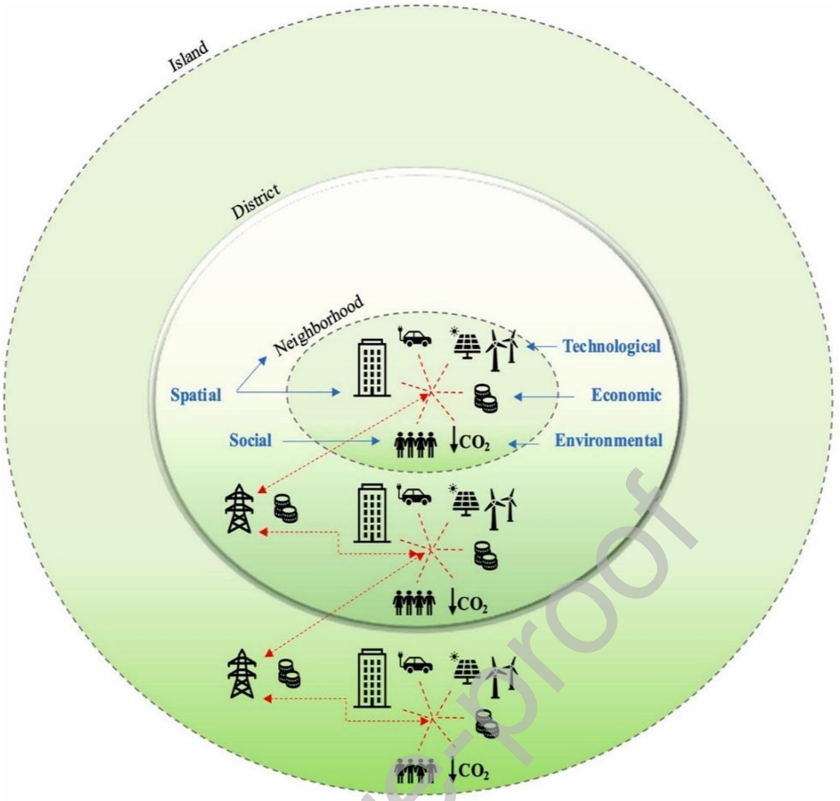
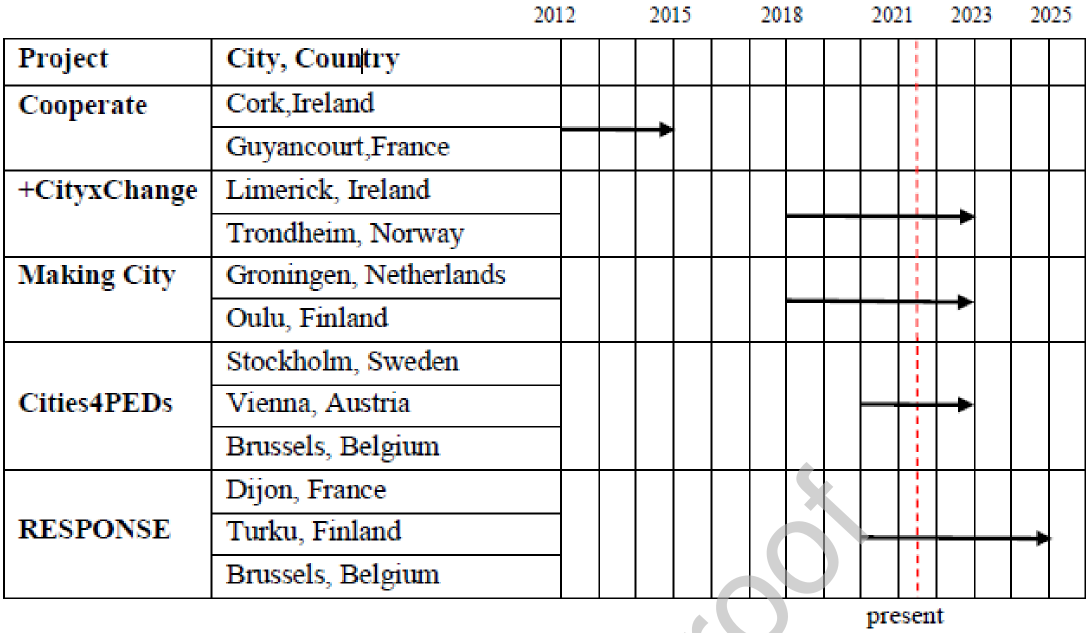


Figure 6. PEDs in Doughnut Economics theory

2.1.4 Projects and Applications with Positive Energy Context

Replying to the PED/PEN trends, the literature highlights the development of multidisciplinary projects to identify the implementation of this itinerary exploring new strategies and high-quality data with well-established methodologies. Giving continuity to preliminary developments and projects, usually within the R&D scope, like R2CITIES [86], CITyFiED [87], REMOURBAN for technical solutions [88] and others revised by Rueda [89] in Figure 7 assessed as good practices in existing projects on ongoing projects.



Project	City, Country
Cooperate	Cork,Ireland
	Guyancourt,France
+CityxChange	Limerick, Ireland
	Trondheim, Norway
Making City	Groningen, Netherlands
	Oulu, Finland
Cities4PEDs	Stockholm, Sweden
	Vienna, Austria
	Brussels, Belgium
RESPONSE	Dijon, France
	Turku, Finland
	Brussels, Belgium

Figure 7. Timeline of PED projects (existing and ongoing) [89]

The initial research developments were focused in particular at the district level with limited interactions in macro-level scales. R2CITIES [86] has been the first recorded project in the PEDs' history to focus on a holistic design based on a multi-criteria decision-making process to identify optimized solutions for retrofitting along with sustainability indicators. On the other hand, the CITyFiED multi-phased project delivered customized initiatives for a comprehensive and sustainable procedure in districts with energy efficiency as its priority.

Leveraging from the experience gained on previously cited projects, Making-City [90] project focuses on the PED design in a six-phase and eight-step process encompassing a decision-making pathway underlining the importance of citizen engagement in building the 2050 vision as a longer timescale to address the city transformation towards low-carbon concepts. An important point to underline is that the Making-city methodology combines the analysis on both district and city levels concerning the regulatory framework, the resources' and data availability. Zhang et al.

[91] analyzed a PED booklet about building types, energy technologies, stakeholders, etc. Bossi et al. [92] adopted the same key criteria in their overview of 100 PEDs strategies.

3 CHALLENGES AND LIMITATIONS OF EXISTING METHODS

Today, PEDs are a promising and powerful concept but they consist only one piece of the urban low carbon and energy puzzle. Hillman [93] emphasizes the lack of socio-technical methods and deficiencies concerning sustainable transformations. Sibilla [94] stresses the importance of the environmental design approaches based on advanced modelling processes for accurate predictions of the energy systems and technologies as traditionally. Thus, the state-of-the-art of the previous section underlines the importance of standardized approaches with different scopes and design alternatives and the introduction of systematic analyses for further investigation. At the same time, most approaches report on national cases and buildings' performance and related measures.

3.1 The Challenge of the 'Urban Scale'

The literature comprises a massive body of theoretical and experimental research devoted to the overall performance of building control (e.g. [95]–[97]). In this context, dynamic simulations with comprehensive tools serve as key approaches to building models with accurate predictions and designs analyzed from different angles. Building energy modelling has been extensively explored in the literature as a means of design, operation and optimization of performance, and design of energy efficiency consisting of a mature research domain.

Nonetheless, in recent years there has been a rising interest in scholars dealing with energy modelling, analysis and optimization at the urban level [98] underlying the complexity of the urban systems for applied research (e.g.. Li et al. [99]). Shi et al. [100] reviewed different methods and design models in a three-step process: (a) data collection, (b) generation, the core of the urban design and (c) optimization.

In reality, districts (and more cities) are important actors in low-carbon and energy transitions as decision-makers to lead to green gentrification, exacerbate inequalities and fight against energy poverty. Hence, PEDs are the evolutionary step following NZEBs to bring technical and financial solutions for collective energy production and storage. The role, thus, of the urban vision and 'community' is to settle long-term energy planning strategies and thorough actions towards 2050 decarbonization.

3.2 The Challenge of Regulatory Framework

Aggregating the PEDs' importance, the missing opportunities for supportive and concrete provisions and the sluggish negotiations, the European Renovation Wave [11] scales up the approaches for integrated solutions (Figure 8).

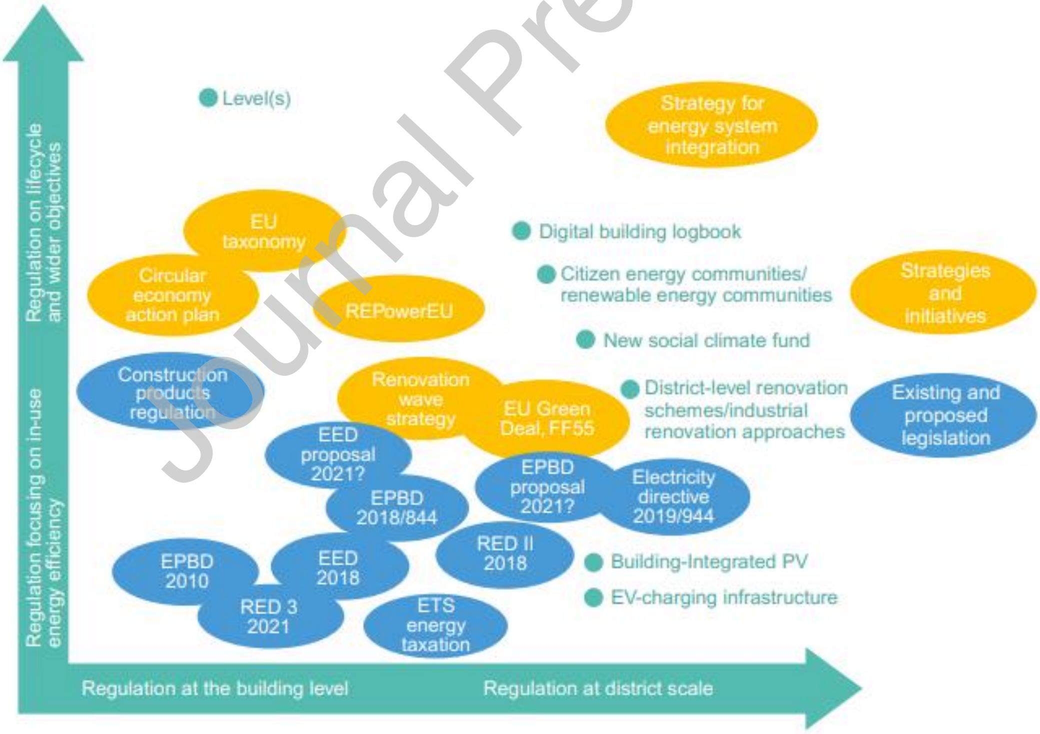


Figure 8. PEDs in a wider policy context

As a promising concept for decarbonization strategies, PEDs could optimize solutions, systems and synergies to reach energy savings and greater emissions reductions beyond zero-energy buildings.

3.3 The Challenge of the Energy System

A PED is characterized by a positive energy balance within a given boundary, however, this definition is not straightforward as it can be geographical or even virtual. Talking about a geographical boundary, the energy system is constrained within a specific perimeter of analysis, a geographical area that does not include other independent energy systems around; this means that the PED achieves a net positive yearly energy balance within its boundaries (in its perimeter) and allows dynamic exchanges (Figure 9, [101]).

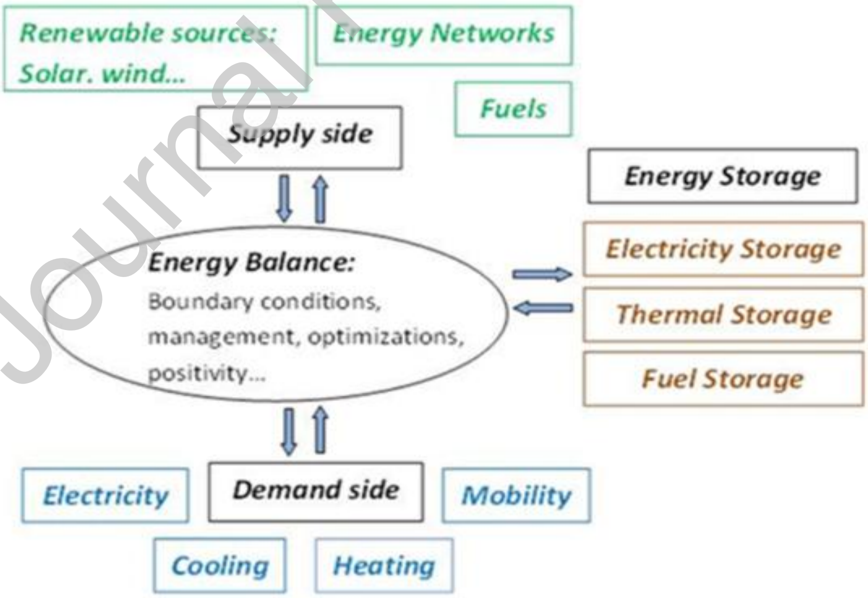


Figure 9. Urban flows in PEDs balance

Talking about an energy system, the design of a physical system to supply energy services for the end-users including all the interconnected components related to the phases of production, conversion, storage, distribution and (final) end use for the citizens is considered.

At the core of a PED is the physical energy system with a pioneer objective: **"A high level of local urban renewable energy and energy efficiency "**. (ANNEX 75 https://annex75.iea-ebc.org/)

The PED energy system is composed of five main elements as proposed in the study of Ahier et al. [102]:

1. **Energy efficiency**: suitable building design and geometry to optimize the level of insulation for the envelope's protection, construction, ensuring energy-conscious user behaviour and others.
2. **Energy carriers**: KPIs calculated to the district boundaries, including energy use for transport inside buildings, infrastructure and other needs.
3. **Renewable energy production:** a twofold approach: a) RES integration into buildings and their immediate surroundings and b) stand-alone production facilities integrated into active or passive systems.
4. **Energy flexibility:** connected to the cost-effective system being reliable across the time scale to meet the peak load demand, the net loads from increased RES use, etc.
5. **E-mobility:** smart charing and enhancement of the EVs' use to supply (e.g. energy back to the grid, V2G to store electricity in batteries, etc.).

3.4 The Challenge of Energy Consciousness and the Societal Aspects

The success of PED implementation cannot be independent of social commitments. Citizens in a PED become prosumers by improving the consciousnesses and accelerating the adaptation and implementation processes. Citizen involvement is seen as a key pillar of the energy transition processes since their interaction with energy systems demand social innovation [103]. To understand the context and the benefits of the governance systems for the PED processes, Potts et al. [104] suggest considering how the system is structured and organized, but also how the structures in the system function. Since different structures and functions of PEDs are interconnected and interdependent, the first step is to deeply understand each identified topic/challenge and the synergy between them in the context of an ever-changing, complex and unpredictable PED system.

At the same time, there is a widespread consensus on the importance of the citizens' and end-users' roles in this transition from passive consumption to active presumption, acceptance and engagement [59]. Halachmi and Holzer [105] emphasize citizen participation as an important component not only to achieving democratic governance processes but also to increasing transparency in the decision process and realising the PED procedure by prioritizing them to integrated city planning.

Koirala and Koliou [106] drew attention to the factors that determine the willingness of local citizens to participate in the design of local energy systems. Paone and Bacher [107] argued that these factors resulted in uncertainty for the prediction of occupant-related energy behavior by creating a gap between the actual and the predicted energy performance of buildings. Massey et al. [108] addressed the challenges from the point of local communities focusing on the lack of citizens' and local organizations' commitment to the energy transition. Secondly, they pinpointed the absence of infrastructure for the transparency of strategies and regulatory framework as a major barrier. Another point includes the shortage of public confidence in new energy models, systems and installations as well as hesitation to adapt themselves to a different reality.

PEDs are a catalyzer with primary and secondary social benefits and a lever for innovative solutions for energy and carbon emission savings in their operational phase. The challenge of social acceptance and the use of technologies require diligent care by the stakeholders to lead to a behavioral change [109]. At the root of a successful case, the development of innovative governance mechanisms and structures are the pillars to activate the communities towards the implementation of this roadmap, reduce energy poverty and fossil fuel dependency and create well-being in healthier environments.

3.4.1 Behavior Modeling Approaches

The comprehensive understanding of the occupant behavior in energy modeling categorizes the approaches basically on two levels of granularity (space- or person-based). The occupant behavior is one of the main challenges, with rising scientific interest (e.g. [110]–[113]) for discrepancies between the calculated and the expected energy requirements in buildings leading to important gaps; the cause, as Menezes et al. [114] argued, is mainly related to misplaced data and parameters in energy simulations. In a recent model generating the detailed thermal energy demand in districts, Kazas et al. [115] accentuated occupant behavior as the most important variable, particular regarding comfort level.

3.5 The Financial and Business Challenges

Zhang et al. [26] identified in their works the vital role of the financial models to bring the clean energy transition resulting in the PED implementation. In the study on the PED analysis and the booklet proposed by JPI Urban Europe [116], it is revealed that the combination of public, private and others (e.g. national or regional subsidies) has been the most common strategy (in more than 20 projects). Only public financing in terms of EU grants or municipality funding is observed in 14 projects out of 60 projects in Europe, 5 projects, which solely depend on private financing strategy, and 8 forwarding with private and public finance combination.

There is no predefined and single business and financial model for a successful PED development, but a combination of different ones is to be defined across the involved parties. This proposal is found on the levers of PED energy systems, therefore, the stakeholders' mapping involved and their interactions with the ecosystem. Indeed, this may turn out to be a difficult process with complexities arising to define the public or private stakeholders, whereas suitable business models are identified. Some typical business models are found in the literature for this topic and noted below (example in [117]):

- A one-stop-shop business model in which a single stakeholder is responsible for the holistic package of services including consulting, energy audit, renovation and follow-up actions.
- The Energy Performance Contracting model enters into arrangements with property owners (of buildings or public infrastructure) by implementing various measures to guarantee energy cost savings compared to a historical energy cost baseline.

3.6 The Data Challenge

Urban-scale modeling tools for energy transition are becoming increasingly available and expected to be a key planning tool for the most effective strategies ad district and city levels to forecast the performance and predictions.

Four categories of data required for this process are usually found in the existing methodologies developed:

1. **Research data**: collecting and underlying the requested data for results' simulation, validation and experimentation associated usually with the metadata.
2. **Operational & observational data**: including curated or raw data arising from the implementation, testing and demonstrations (by pilots, for instance) or data derived from qualitative (or quantitative) surveys or on-site analysis, interviews, etc.
3. **Monitoring & evaluation data**: reporting and monitoring of the progress of particular phenomena or observations.
4. **Documentation & reusable knowledge**: this concerns general and specific documentation of the project and demonstration/implementation projects, including tools, methods, instruments, software, and underlying source code needed to replicate the results.

Nevertheless, many of these emerging urban-scale models are largely demand-focused for predictions of annual energy demand or quantification of efficacy of energy savings measures. Simulating the spatiotemporal patterns of building energy demand at an urban scale remains complex requiring large amounts of data with interactions, for instance, buildings and occupants, etc.

4 CRITICAL REVIEW AND MISSING POINTS

Looking from a more critical angle at the barriers analyzed in the previous section, it is concluded that there is hardly an ad hoc theory replying to the PED standards and characterization and that all the components presented in the existing literature still are under exploration. Developing a comprehensive method for PEDs is not an easy or linear task and includes complex knowledge and governance mechanisms. Despite the multiple efforts to classify and categorize the modeling techniques for energy balance, for instance, deterministic and stochastic approaches, to space or time-based and others, the difficulties of understanding the interactions of urban systems prevent the common acknowledgement of a single method.

Challenges associated with socio-economic, administrative, cultural, legislative and other perspectives have important relevance in all PEDs [46]. The examination of the available tools and methodologies emphasizes five commonly acknowledged steps beginning with a baseline and diagnostic analysis in line with the socio-economic and spatial characteristics of the studied cases, the identification of energy needs (calculations on heating/cooling/electricity and similar requirements), the tools for measuring the balance on demand and supplies, the scenario and sensitivity analysis and to end up the strategic planning of concrete actions and is not interpreted in linear processes but more complex procedures (Figure 10).

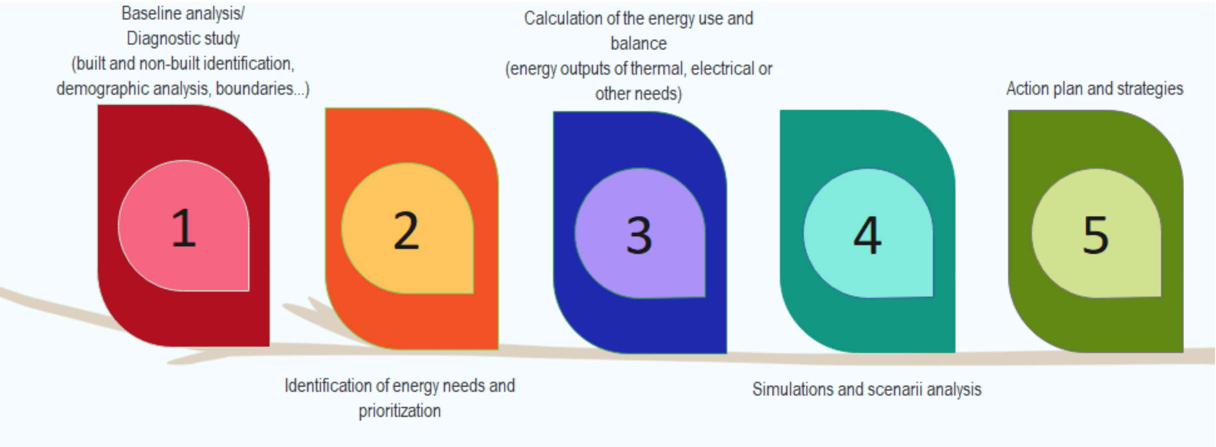


Figure 10. Commonly acknowledged steps in PEDs' methodologies and tools

4.1 The Importance of Citizen-oriented Methods and Tools

Limited research and methodological development have been developed in the specific field of PEDs. So far, technological innovation gained stronger attention rather than the perspective of citizen empowerment and engagement to ensure PEDs' functionality. A rigorous emphasis on citizens observing their needs introduces an aspect of the project's democratization and co-creation in a multi-stakeholder ecosystem.

To enable social innovation in the PED process, Farazmand [118] explores **'capacity building'** as activities to strengthen abilities and the knowledge and experiences transfer. Unquestionably, co-design strategies for the commitment of local actors enable the integrated and comprehensive planning of PED communities; yet, social aspects are crucial for the interrelation of urban systems and stakeholders to bring innovation in PED design, as also developed in the SET Action Plan (Figure 11) [36].

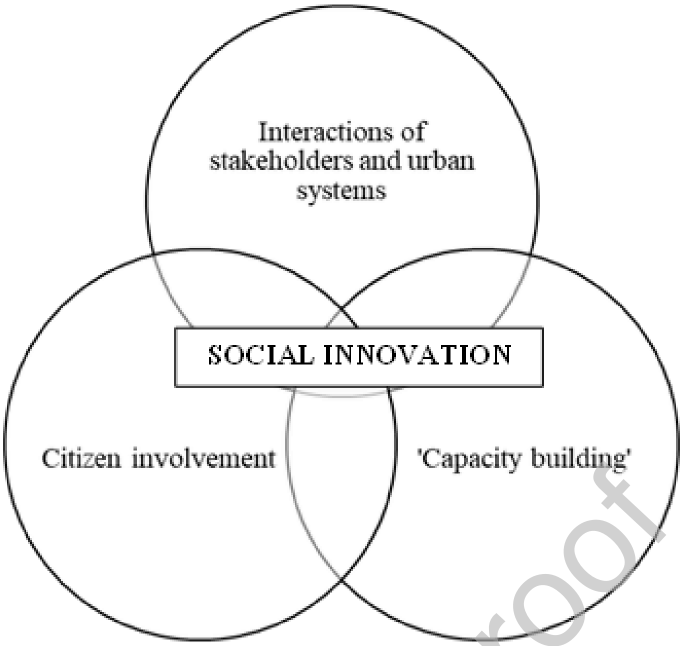


Figure 11. Elements of ‘social innovation’ in PEDs’ design (adapted by [25]).

Insightful cases in this field are analyzed in a benchmarking study of Norwegian projects provided by Baer et al. [119] concerning stakeholder engagement, citizen participation and the capacity building to orchestrate the elements of the ‘social innovation’ in PEDs’ communities aligned with the technological advancements.

The role of people-oriented PED design is also argued by Bossi et al. [59] and the collected cases, as summarized in JPI Urban Europe’s report [120], with the identification of key factors for successful implementation, from which we underline the importance of stakeholder involvement (Figure 12).

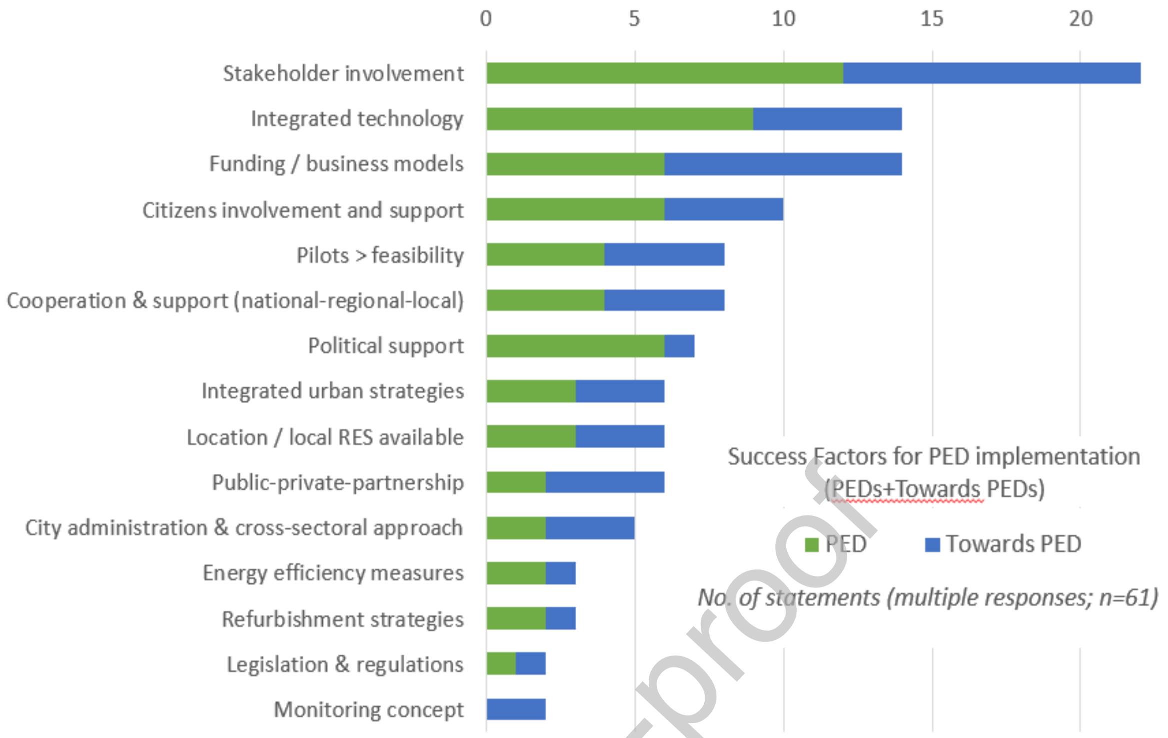


Figure 12. Successful factors for PED implementation (Bossi et al. [121])

Hence, a successful PED requires collaboration with citizens and the development of effective mechanisms of governance. Simultaneously, political support is necessary to activate the national programs and regulate the existing (sometimes conflicting) framework and release new funding opportunities for adequate sources introduced in the concepts. Prioritizing the human ecosystems, the structural changes are fostered far from the monolithic approaches of technical components to accelerate the PED deployment and ensure their operation.

Future research is inquired into how the bottom-up initiatives will be incorporated for the co-creation of PED designs in a comprehensive ecosystem combining the technical and socio-ecological systems for renewable energy and long-term transitions.

4.2 Towards Cross-Sectoral Approaches for PEDs

The analysis of reviewed methods and tools reveals a general framework of KPIs and grouped factors under hypotheses and basically developed under the 'umbrella' of technical approaches with limited consideration on social dimensions and human-centric approaches. In some cases, an overlapping of similar sustainable parameters of the urban metabolism is observed, while others focus on the combination of technologies and financial challenges neglecting the importance of users [122] and providing monolithic outcomes without robust assessment. A key element for the contribution of people-oriented approaches is the 'energy communities' and the collectively-driven actions to increase public awareness and attract investments for paving the clean energy transition way.

The analysis emerges the benefits of cross-sectoral planning beyond the technical challenges to include other sustainability criteria, e.g. social or economic perspectives. The study highlights the emergence of new actors and stakeholders to enhance and develop innovative governance mechanisms and structures, but also the communication campaigns to mobilize local stakeholders for the benefits of energy efficiency on different scales. Recognizing the value of citizen empowerment, the relevant projects trigger this engagement but none of the identified ones provides evidence for sustained and meaningful evidence on the approach. In this sense, strategic planning with organizational activities for stakeholders' guidance at all stages of the planning process is mandatory for problem-solving objectives.

More horizontal and cutting-edge approaches to better understand and include the role of citizens in making communities a sustained success is expected.

5 CONCLUSIONS

PEDs are an increasingly developed, promising but challenging initiative in the European Member States, explained as a community (basically ‘district’ or ‘urban block’) producing more energy than consuming. Primordially, the target is to facilitate the design and implementation of concrete strategies across Europe leveraging energy production, efficiency and flexibility to achieve decarbonization by 2050.

Previous research concludes with the centralization of technocratic, engineering and not democratization approaches. The dashboard of challenges and restrictions is explored in this work with the acknowledged ongoing projects and models published. Pragmatically, the existing concepts are too simplified and fail to consider the interrelations of urban systems and their contextual factors. The literature roadmap unveiled the gaps in governance mechanisms, citizen-participatory processes and bottom-up methods to develop synergies and co-creative standards for the PEDs conception and implementation. Apart from this, the analytical scheme of processes revealed the need for strategic planning aligned with social, technical, financial and regulatory dimensions, but also the substantial challenge for data accessibility and interoperability.

The non-technological PED solutions for shared information and citizen empowerment are considered in a broader perspective as key facts for PED-related projects to speed up the decarbonization reaching the COP21 ambitions. Existing experiments on booklets and implemented cases prove the lack of comprehensiveness and consistency of PEDs within sustainable criteria, basically human-centric ones. In reality, the complexity of the urban systems’ identification in a dynamic way makes the PEDs’ operationalization sophisticated, but insightful in its inherent context.

The study contributes to the literature by leveraging the importance of knowledge gaps recognizing the systemic nature of the urban systems and discussing the limitations and challenges of available assessment metrics of PED-related concepts. Currently, several fragmented methodologies are identified in the literature on different levels of assessment, usually technologically oriented or within other scopes, e.g. modelling/simulation, GIS-based, optimization, etc. In this sense, the PED approach should be consolidated into integrated and systemic visions building dynamic aspects to encounter the decarbonization ambition but in the macro-economic horizon.

Together, the review serves to provide an in-depth analysis of what lenses PED design and conceptualization and supports the cross-sectoral angles to prioritize the users' role aiming to sustain communities.

Declaration of Competing Interest

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

NOMENCLATURE

Acronym	Definition
CBA	Cost-Benefit Analysis
CITyFiED	RepliCable and InnovaTive Future Efficient Districts and cities
COVID	Coronavirus Disease
EC	European Council
EED	Energy Efficiency Directive
END	Energy Neutral Districts
EPBD	Energy Performance of Buildings Directive
EPN	Energy Positive Neighborhood
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas Emissions
GIS	Geographical Information Systems
ICT	Information Communications Technology
IEA	International Energy Agency
JPI	Joint Programming Initiative
KPIS	Key Performance Indicators
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MCDA	Multi-Criteria Decision Aid
MS	Member States
NPV	Net Present Value
NZEB	Net-Zero Energy Building
NZED	Net-Zero Energy Districts
PEB	Positive Energy Block
PED	Positive Energy District
PEN	Positive Energy Neighborhood
R&D	Research & Development
REMOURBAN	REgeneration MOdel for accelerating the smart URBAN transformation
RES	Renewable Energy Sources
R2CITIES	Renovation of Residential urban spaces
SET	Strategic Technology Plan
V2G	Vehicle to Grid
ZEB	Zero-Energy Building

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