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Multi-dimensional self-assessment matrix and scoring system for Positive Energy Districts

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Introduction: A predominant portion of current Positive Energy District (PED) projects focuses on technical advancements, often neglecting non-technical aspects, which can hinder a just energy transition. This raises the question: How can PEDs be assessed to ensure a just, inclusive, and context-sensitive energy transition beyond technical solutions?
Methods: This study develops a cohesive approach that embeds the multiscale, multisectoral, multi-component, and multi-actor nature of PED development. A multi-criteria PED Matrix was created and refined using Natural Language Processing (NLP) and expert feedback to evaluate and benchmark PEDs across eight dimensions: social, governance, technical, process, environmental, legal, financial, and managerial.
Results: Five European pilot cases (in Austria, Sweden, and Türkiye) were assessed using the matrix, revealing context-specific strengths and capacity-building needs and enabling cross-case learning and comparison.
Discussion and conclusion: The PED Matrix supports self-assessment and co-design processes, helping local stakeholders identify weaknesses, required competencies, and lessons from other PED-related cases, promoting inclusive and context-sensitive energy transitions.

KEYWORDS

Positive Energy Districts, PED Matrix, self-assessment scoring system, collaboration pathways, quadruple helix

1 Introduction

Buildings account for approximately 30% of global final energy use and more than 55% of global electricity consumption (IEA, 2019). The concept of Positive Energy Districts (PEDs) was initially developed with a focus on ensuring individual buildings achieve zero-net energy use. The concept has evolved to include entire neighbourhoods and city districts. The European Union's "Positive Energy Districts and Neighbourhoods for Sustainable Urban Development" program was launched to support the planning and deployment of 100 PEDs in Europe by 2025. However, this expansion has revealed key gaps—namely, a lack of attention to social dimensions and community participation in PEDs as well as the absence of comparative parameters needed to form cohesive and holistic understandings of their development.

Social factors are critical yet under-researched topics in the development of energy projects (Baer et al., 2021; Brozovsky et al., 2021; Krangsås et al., 2021). Similarly, critical social

dimensions are also often under-researched and insufficiently addressed in PED development (Hearn et al., 2021; Nguyen and Batel, 2021; Sareen et al., 2022; Sassenou et al., 2024; Ertelt and Carlborg, 2024). Corsini et al. (2019) conducted a bibliometric analysis of 74,932 research publications, revealing that while technological advancements in energy studies are thoroughly explored, social dimensions, particularly public participation and community involvement, represent a relatively minor focus. PED projects incorporate ambitious environmental goals, but they are often significantly limited when it comes to including diverse social groups (Hearn et al., 2021; Nguyen and Batel, 2021; Sareen et al., 2022; Sassenou et al., 2024). Achieving sustainability requires not only technological innovation but active citizen engagement and inclusive decision-making processes as well (Ahvenniemi et al., 2017; Sovacool et al., 2019; Angelakoglou et al., 2020). Successful PEDs need to go beyond tokenistic engagement by fostering genuine participation, where citizens act as co-creators or energy solutions, rather than passive recipients (Olivadese et al., 2020; Nasya and Vurucu, 2024; Akkaya and Erdoğan, 2019). The success of PEDs depends not only on technological advancements but also on fostering energy citizenship. The effective implementation of PEDs and their potential to reduce energy demand and greenhouse gas emissions depends on the prioritisation of community engagement. Such participation must be accessible and equitable. The focus needs to be on dismantling barriers to engagement, while aligning top-down governance with bottom-up empowerment through structural changes such as forming energy communities and cooperatives (Magrini et al., 2020; Bossi et al., 2020; Ahlers et al., 2019). Strategies that reflect legal frameworks, stakeholder needs, and local capacities are thus imperative for PEDs to be accepted, effective, and socially sustainable.

By empowering citizens to become active prosumers (Magrini et al., 2020) and facilitating their involvement in the planning and implementation process (Olivadese et al., 2020), PED projects can achieve greater acceptance, wider applicability and long-term sustainability. Prosumers could play an active role in PEDs, by evolving from the role of consumers to active producers in the energy sharing context. The term "prosumer," coined by Toffler (1980), describes individuals who both produce and consume goods or services. While Toffler envisioned prosumers as central to a post-industrial economy, the modern understanding of prosumers encompasses a wider range of activities. In energy systems literature, prosumers are defined as energy consumers who also produce energy, typically through distributed renewable energy technologies such as solar panels, wind turbines, or combined heat and power systems (Parag and Sovacool, 2016). To activate the role of citizens and empower them to play their part in the shaping of the PED, clarity is needed in the characterization and assessment of a PED by different groups, including citizens (energy demanders) and prosumers (group of people who partially can cover the energy demand locally). A prosumer can play an important role in the concept of PEDs, however their characteristics are not yet fully explored, especially those of non-technical prosumers.

Inclusive, context-sensitive, and participatory approaches are essential to ensuring the contribution of PEDs to the just energy transition. This requires integrating local cultural, historical, and social factors into project aims, design, and implementation (Clerici Maestosi, 2021), ensuring that energy systems are embedded within the economic conditions of communities. Consequently, energy production, consumption, and sharing need to be embedded in the historical, cultural, or landscape constraints, the urban fabric, and the presence of previous programs in the selected area (Maestosi et al., 2021). This means PED development needs to build on collaborations with stakeholders and citizens, work on their social and financial barriers, and guarantee a feasibility that is worth the effort put forth by the participants. Failing to address non-energy-based considerations such as social, economic, and environmental factors that extend beyond energy metrics can result in a lack of alignment across projects, making it difficult to establish benchmarks and assess performance. Several EU-funded projects currently deal with this topic while numerous funding schemes support implementation, creating opportunities to design inclusive PED projects that can have a positive impact on the just energy transition (Brozovsky et al., 2021; Maestosi et al., 2021). Thus, collaborative approaches and new partnerships are essential to address the social, behavioural, and participatory dimensions of the energy transition, which place project actors under even more pressure. New evaluation tools centred on a cohesive PED approach are increasingly needed for both implementation and research (Nasya et al., 2024). The increasing number of terminologies, targets, key performance indicators (KPIs), and other elements makes it difficult to compare methodologies or projects effectively (Brozovsky et al., 2021; Maestosi et al., 2021). A comprehensive self-evaluation framework can provide clarity, guidance, and comparability, while addressing social and participatory aspects to support inclusive PED development.

A variety of global frameworks and indices assess urban sustainability using composite indicators. Many are rooted in the triple bottom line of People, Planet, and Profit (social, environmental, and economic) with additional dimensions as needed. The ISO 37120 Sustainable Cities standard defines 46 indicators under themes ranging from economy, education, and energy to governance, health, transportation, environment, and more (ISO, 2014). These standards aim to allow any city, regardless of size or development level, to measure performance in a comparable and verifiable manner. Similarly, the Reference Framework for Sustainable Cities (RFSC) in Europe provides an online toolkit with a broad collection of city indicators (28 indicators, including share of renewable energy in overall consumption) for cities to tailor their own monitoring set (Smart Cities Dive, 2025). Research-driven frameworks such as CITYkeys (an EU Horizon 2020 project) explicitly include governance and innovation aspects. CITYkeys developed and validated a KPI system for smart cities with five major themes: People, Planet, Prosperity, Governance, and Propagation (the last referring to scalability/replicability of solutions). A 2020 systematic analysis of 67 urban sustainability assessment initiatives encompassing 2,847 indicators revealed clear biases in what is measured (Merino-Saum et al., 2020). Notably, social aspects (such as quality of life, access to services, education, and health) received the greatest emphasis, accounting for about 46% of indicators, while environmental aspects represented about 24%. In contrast, governance and political factors (participation, inclusiveness, and institutional capacity) made up only around 4% of the indicators on average. Likewise, issues of gender equity and distributional justice were largely overlooked in most indicator sets. It was concluded that while urban indicator frameworks commonly address current needs and resource status, they rarely tackle political and equity questions such as civic engagement or distribution of costs and benefits. One of the earliest global approaches to assess and validate indicators is the Green City Index (Siemens/EIU), which scores cities on

environmental categories such as CO_2, energy, buildings, transport, and waste. Cities receive both overall and category scores, enabling cross-city comparison and best-practice learning (The Green City Index, n.d.). Similarly, the Arcadis Sustainable Cities Index uses a scoring system structured around "People, Planet, and Profit," later adding a "Progress" dimension to assess improvement over time (The Arcadis Sustainable Cities Index, 2024).

These frameworks demonstrate how scoring aggregates diverse data into accessible rankings for different uses in the urban development or transformation context. The systematic review of PED-related indicator studies noted that most PED indicator sets can indeed be mapped to the classic three pillars of sustainability (environmental, economic, social), but these sets are not yet consolidated or consistent across projects (Orova and Reith, 2024). This lack of a standardised framework means each PED or smart-energy community project might choose a different mix of KPIs, making comparisons and shared learning difficult. This also makes cross collaboration with citizens more difficult, given that citizens and prosumers could participate in different energy projects, e.g., an energy community and a PED project. Scholars argue about developing integrated, holistic assessment tools specifically tailored to positive-energy communities. Kozlowska et al. (2024) observe a clear need for "integrated district-level tools and guidelines" that account for the multidisciplinary complexity of PEDs. So far, there is a lack of sufficient studies regarding the systematic comparison and evaluation of different PEDs. On one hand, PEDs are complex and related to many aspects of the urban transition. On the other hand, there are several PEDs or PED-related projects, consisting of large volume of information (e.g., data, reports) which are difficult to categorise. It would be beneficial, especially for the general public (e.g., citizens to be engaged or prosumers to be empowered as stakeholders) and policy makers, to have a framework that enables the comparison and assessment for various PED contexts.

The aim of this study is to describe the development of the PED Matrix designed to include the often-overlooked non-technical dimensions of PEDs, including social, governance, managerial, legal, and financial aspects. This ambition is aligned with the mentioned indicators in other urban research, development, and transformation frameworks listed above, as well as the aim of helping citizens compare and assess. The methodology consists of applying Natural Language Processing (NLP) to analyse unstructured textual data, which ensures a systematic and data-driven approach to identifying PED themes and aspects. Developed through the analysis of existing PED projects, the PED Matrix establishes a framework consisting of eight core aspects, each further detailed by five sub-aspects, which are aligned with energy transition objectives. This structure supports project teams and partners in mapping and scoring their capacities in a self-reflective way. By organising complex data and offering a common language, the matrix facilitates self-assessment, helps identify development needs, and enables benchmarking across various contexts. It also promotes a balanced perspective by yielding equal importance to technical and social components of PEDs. As a practical and adaptable tool, the PED Matrix contributes to more inclusive and effective PED strategies. It has been tested in five pilot cases within the PED-ACT project, with the aim of enhancing mutual learning and knowledge exchange among diverse PED initiatives.

In this paper, Section 2 details the overall research methodology and outlines the information required as input for assessment. Section 3 depicts the contexts of the case studies. Section 4 presents the main results for the eight aspects, while Section 5 provides a discussion and Section 6 offers the conclusion.

2 Materials and methods

2.1 Overall research methodology and PED Matrix aspects

Figure 1 illustrates the overall research approach. The collaborative development is based on quadruple helix model, which encourages collaboration among academia, government, industry, and civil society. The Natural Language Processing method is applied to analyse unstructured textual data to ensure a systematic and data-driven approach to identifying the PED aspects which are aligned with the three main pillars of sustainability: social, economic, and environmental.

PEDs are understood as socio-ecologic-economic systems, shaped not only by technology but also by social dynamics, policies, and the natural environment. The energy transition leads to physical changes in the built environment, increases the availability of energy-related data, and influences people's behaviour. For these changes to be effective, they must be supported by a policy and governance framework that enables their operation. Interconnected layers of a PED system are grouped into three categories: hardware (such as renewable energy systems and infrastructure), software (including digital tools and monitoring systems, as well as public awareness and involvement), and orgware (governance models, regulations, and cooperation methods). This cohesive approach supports the development of the PED Matrix that are energy-positive, socially inclusive, and well-integrated into broader urban systems.

2.2 Quadruple helix model

PED projects can benefit from the quadruple helix approach (Schütz et al., 2019; Carayannis and Campbell, 2009) by bringing different actors together in a collaborative mode for sustainable innovation (Arnkil et al., 2014). Community involvement in innovation systems, rooted in democratic and social innovation theories (Fung and Wright, 2011; Mulgan, 2006), is crucial for addressing complex societal challenges. In the energy transition, understanding local energy practices and community values is essential for effective solutions (Sovacool, 2014), especially for creating a meaningful participation and empowerment scheme. The PED development also includes multiple sectors (Schneider, 2023), including the energy, buildings, mobility, and public sectors. Research highlights challenges in coordinating across sectors due to differing priorities and metrics (Bryson et al., 2006; Palm and Reindl, 2018). Energy transition projects frequently fail because they neglect community needs, reflecting Arnstein's critique of tokenistic participation (Arnstein, 1969). Effective community engagement requires co-creation (Prahalad and Ramaswamy, 2004) and co-design (Sanders and Stappers, 2008) approaches that recognise community members as local knowledge experts (Fung, 2006), while acknowledging internal community disparities and power dynamics (Young, 2002). Successful PED development demands boundary-spanning (Williams, 2002) approaches that bridge top-down

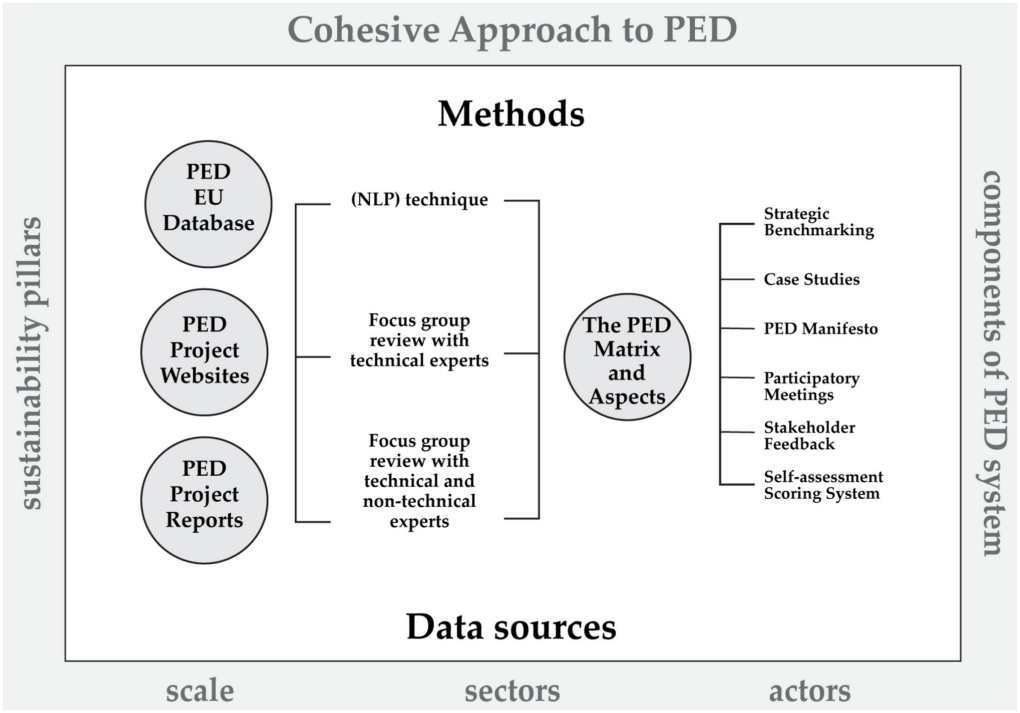

FIGURE 1
Research methodology of the study.

institutional capacity with bottom-up engagement (Ansell and Gash, 2008) through both formal mechanisms and grassroots networks. However, awareness alone is insufficient and effective engagement must address structural barriers, create meaningful roles (e.g., prosumers), and develop supportive social norms for sustained community involvement (McKenzie-Mohr, 2011).

The involved sectors typically include the energy sector (renewable generation, grids), the building sector (construction, retrofitting), the mobility sector (sustainable transport), and the public sector (local authorities, policy frameworks). The PED Matrix addressed the need for cross-sector collaboration in creating a framework of aspects, which allows the organisations of tasks related to a PED in a comprehensive way. In the pilot cases of the PED-ACT project, local partnerships from the four categories of the quadruple helix either participated directly in case development or were invited to provide feedback and contribute to discussions. Although the quadruple helix approach is not always reflected in the internal dynamics of each case, it is ensured through the overall PED-ACT partnership structure, which includes all four actors. At the same time, the results of the self-assessment reflect the collaboration gaps and suggest that sectors and actors need to be more involved (see Section 5 Discussion to Section 6 Conclusions). Although the citizen-driven case of the energy community in the Austrian pilot brings academia, industrial, and citizen partners together, it still demonstrates difficulties in reaching decision making authorities such as municipalities. The Swedish cases present a collaboration culture between municipality, academia, and industry, yet lack the inclusion of citizens living in rented flats in the buildings. In the Turkish cases, the collaboration on energy topics between the four actors is not yet established. All these variations are reflected in the scoring system.

2.3 Natural Language Processing method

The exploration of PED project sources such as websites and public documents played a crucial role in developing the matrix tool, particularly given the current process of planning, deploying, and replicating 100 "Positive Energy Districts" by 2025 to achieve climate-neutral cities (Bossi et al., 2020). The research included PED projects at various stages of implementation and identified 79 such websites for screening. Following that, the search was restricted to websites in the English language and excluded websites with fewer than 200 words. These restrictions yielded 33 PED project websites from which a web scribing was carried out. Their public documents were also assembled to form the collection consisting of a total of 55 text files. Given the diverse implementation of PED initiatives across Europe, the data generated often existed in textual and project-related formats (with less comparability). To resolve this challenge, an NLP technique and topic modelling was used to analyse unstructured textual data from PED project websites and reports, which were primarily sourced from the PED-EU-NET database in 2023. This method aided the identification of the PED topics that constituted the initial inputs to the PED Matrix (Han et al., 2024; Han et al., 2023). The algorithm Non-Negative Matrix Factorization (NMF), which was used in this study, has demonstrated its ability to outperform other methods such as LDA, given that the topics generated by NMF were found to be more interpretable and in better alignment with previous literature (Gupta et al., 2021). Additionally, an analysis on the implementation of smart city projects revealed eight distinct thematic areas: social, institutional, partnership and resource management, scheduling, and execution, financial, technology, political, and environmental (Gupta et al., 2021). These were then used to provide benchmarking aspects

and a discussion basis for forming PED-specific themes. Another traditional algorithm, Latent Dirichlet Allocation (LDA), was used on the same data to cross-check the consistency of NMF-generated topics.

The modelling results from the NMF and LDA algorithms were initially summarised to extract preliminary topics based on the 10 most representative words in each thematic area. In LDA, the top 10 words are those with the highest probabilities in that topic's word distribution, while in NMF, they are the ones with the highest weights in that topic vector. This was followed by merging similar topics from the two algorithms by grouping semantically similar words. Topic names were updated using these words to ensure that they remained consistent with the topic name. Seven distinct topics were found, with each topic representing an aspect of the matrix and these words serving as the corresponding elements. Once the aspects and elements were extracted, they were shared within the PED-ACT partnership to collect feedback for revision. Afterwards, the matrix was further shared with the public, including stakeholders within the international DUT framework and the European PED-EDU-NET network, to gather feedback and refine the matrix. This collaborative process resulted in the final version of the PED Matrix consisting of eight main aspects (Han et al., 2024), where governance and managerial are two distinct aspects, as opposed to combining the managerial aspects under governance. The finalised list of aspects is as follows: social, process, technical, governance, environmental, legal, financial, and managerial. These are further described in Table 1.

2.4 Self-assessment scoring system

The PED Matrix is a tool designed to organise and analyse PED-related data in a way that supports benchmarking and offers a broader perspective on diverse PED initiatives. It enables stakeholders to build and/or expand their analysis and capacities by recognising that energy transition efforts need to address both technical and social aspects with equal importance. Building on this foundation, the matrix has been expanded into a self-assessment scoring system to reflect on the case framework with the PED Matrix perspective.

As elaborated in Section 1.2, there is a lack of a framework that supports evaluation, reflection, and comparative analysis for PEDs. The energy transition scoring system allows reflection on the project, mapping local capacities and analysing whether capacity building or enhanced partnerships are needed to address the respective PED aspect. The scoring system provides a comprehensive framework for collaborative characterization of PEDs, enhancing their comparability and facilitating implementation. This approach remains responsive to changing external conditions.

The energy transition scoring system was formulated for each of the eight PED Matrix aspects (see Table 1), with five topics or questions detailing the criteria to be assessed for each aspect, in a qualitative manner as described in Table 2. A numerical point system ranging from 0 to 3 is assigned for each criterion. A score of 0 indicates that the criterion is entirely missing in the case district, 1 point signals limited identification or availability of the criterion, and a score of 2 represents a moderate level of inclusion or identification. The highest rating, 3, indicates a high or comprehensive degree of inclusion or identification of the respective criterion in the assessed case. The study is based on a survey that involved an interview guide (Table 2). The respondents, consisting of the local stakeholders involved in the project, were asked questions regarding the analysed pilot case in the PED-ACT project between April 2024 to November 2024. The process is illustrated in Figure 1, and the result summary is presented in Table 3.

Although the study includes five pilot cases, the findings may not fully reflect the diversity of PEDs across Europe or globally, as this was not the intention of the study. The scoring system is grounded in the empirical evidence presented in the researched cases of this study. The subjective descriptors (limited, moderate, and high) were harmonised and cross-referenced across the five cases examined. However, the evidence supporting each dimension and its subcategories was not further elaborated, such as the number of public meetings held. The rationale for the scoring process was documented comprehensively for all cases, dimensions, and subcategories and summarised in the keywords for Table 3. The scoring system relies on self-evaluation by local stakeholders, which could introduce subjectivity and bias into

TABLE 1 Main aspects of PED matrix.

PED matrix aspects	Description
Social inclusion	The active involvement of citizens and communities in the planning and implementation process need to be ensured, while also addressing social equity and the equitable sharing of the benefits of the energy transition
Governance	Clear governance structures must be established to facilitate collaboration among stakeholders, while also ensuring transparency, accountability, and inclusive decision-making
Technical solutions	Energy-efficient technologies, renewable energy systems, and smart grid solutions need to be implemented, while also ensuring that technical designs remain adaptable and scalable to meet future needs
Process continuity and flexibility	Ensuring access to a wide range of expertise can become significant, including the management of complex challenges, revitalisation of neighbourhoods, resolution of technical limitations, navigation of legal or heritage-related constraints, and mitigation of project risks
Environmental integrity	Minimising the ecological footprint of PED projects and aligning them with local ecosystems, prioritising nature-based solutions, and reflecting environmental priorities from the local to the continental level, can help inspire community participation
Financial viability	Securing funding and ensuring the economic sustainability of PED projects necessitates the exploration of innovative financing models, such as public-private partnerships or community energy funds
Managerial stability	The development of effective project management strategies is essential for ensuring timely and efficient implementation. The monitoring and evaluation of progress allows for the adaptation of strategies as required

TABLE 2 Benchmarking criteria for the self-assessment scoring system.

Aspects	Questions
Social	How intensely were the stakeholders/citizens engaged and included in the energy transition process? Are social barriers identified for the energy transition process? Is there social interaction in the energy transition project? Is the cultural identity integrated into the pilot development? Are vulnerability topics integrated into the project?
Process	Is PED process information clear and available? Are project phases assessable? Is data accessible and assessable for stakeholders and the community? Are the contacts of those responsible accessible? Does the project team have the capacity to react flexibly in unforeseen situations?
Technical	Are energy efficiency measures implemented? Are renewable energy solutions integrated? Are there energy storage and flexibility in the pilot area? Are there smart devices that allow user interaction? Is the energy balance optimised?
Governance	Is a clear governance structure established? Is the project contributing to the common good? Are governance practices transparent? Are there measures for faulty governing? Is there an alignment with other strategies?
Environmental	Does the project lead to a reduction in resource consumption? Does the project lead to a reduction in carbon emissions? Are there circular economy practices? Is sustainable mobility integrated? Is biodiversity integrated?
Legal	Does the project comply with laws and regulations? Does the project comply with building codes and land-use regulations? Does the project team have access to legally proven solutions? Does the project comply with Citizen Data Privacy and GDPR? Does the project resolve legal barriers?
Financial	Do the project partners have access to funding? Can the partners resolve the financial barriers? Is financial equity and accessibility guaranteed? Are sustainable business models adopted? Is there a reinvestment plan?
Managerial	Is the managerial capacity sustained? Is stakeholder engagement anchored in the management plan? Is the decision-making process clear? Is capacity building and training anchored in the management plan? Is the management done by a legal entity?

the results. In this project, self-evaluation and assessment were crucial for partners and teams to assess their case status and quantify strengths and challenges across teams, stakeholders, and other PED cases. This serves as an essential self-reflection step.

The evaluation aims to support self-organisation and address PED-relevant topics through consultation, co-creation of new solutions, or introducing new partners to collaboration. The scoring system results are not definitive but an interim sequence to facilitate task assignment in the PED process. For the validation of these results, projects can adopt multi-source validation systems, such as triangulation of perspectives, or seek validation from external sources. Additional evidence and documentation of evidence can assist replicators and users of the scoring system in obtaining validated results. Statistical validation methods process improvements and adaptations may be necessary in other replication cases. In this project, it was necessary to see the compliance of the selected pilots with the PED Matrix. The cases in this study are in the preliminary phases of PED design. In this study, the scoring system was used to preliminarily assess the pilots. In a PED process, the scoring system could also be used for interim and final assessments in the PED development and implementation phases. For this kind of new use, the validation methods must be adopted accordingly.

This study examines five cases across three countries: Schönbühel-Aggsbach in Austria, Borlänge and Umeå in Sweden, and Ankara and

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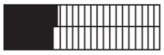
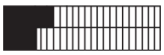
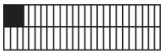
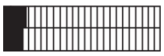
TABLE 3 Keywords and self-evaluation scores for the five cases on the eight PED aspects.

PED aspects	Karşıyaka	Ankara	Schönbühel-Aggsbach	Umeå	Borlänge
	Moderate Need for social inclusion, capacity building, and cultural identity integration	 **Limited** Social barriers; preliminary social inclusion; need for capacity building	**Comprehensive** Good social and cultural identity integration; need for social inclusion	**Moderate** Established social inclusion; need for external help for further improvement	**Moderate** Good integration of cultural identity; established social inclusion and interaction
Process	 **Limited** Good data accessibility; preliminary clarity on the PED process; need for serious efforts	**Moderate** Good knowledge and experience; given clarity and availability	**Moderate** Need for clarity and availability on the PED process; need for knowledgeable partnership	**Comprehensive** Well-covered information and data access, need for project assessment	**Moderate** Need for support and reflection, need for project assessment
Technical	 **Limited** Starting to invest; need for support	**Moderate** Well served techniques; good knowledge on energy topics; need for partners	**Limited** Need for technical expertise	**Comprehensive** Well-established collaborations; need for a detailed pilot structure	**Moderate** Good energy solution; need for a plan to become a PED
Governance	**Moderate** Positive self-assessment; need for deeper analysis; no measures for faulty governing	**Moderate** Established and clear structure; good transparency; need for training and capacity building	**Moderate** Structures set up; need for further elaboration	**Moderate** Well-established schemes; no structures for a specific pilot	**Moderate** Partly established; need for reflection and assessment; need support for integration
Environmental	 **Limited** Municipal energy efficiency evaluation in 2010, but no follow-up; no carbon emission reduction; minimal waste collection; no sustainable mobility and biodiversity integration	**Limited** Good knowledge and overview; established circular economy practices; need for support	**Moderate** Prioritised aspects; need for support in circular economy (CE) and biodiversity; untapped sustainable mobility	**Comprehensive** Good basis for environmental actions; need for reflections on the environmental actions and synergies	**Comprehensive** Well-established CE and biodiversity; need for improvement in sustainable mobility
Legal	**Limited** Public organisations involved; need for support for local actors	**Moderate** Good compliance; need for training and capacity building	**Moderate** Established rules; possible but infeasible compliance; need for support and training	**Comprehensive** Strong clarity; need for a reflection session	**Moderate** Access to legally proven solutions; need for review and elaborations

(Continued)

TABLE 3 (Continued)

PED aspects	Karşıyaka	Ankara	Schönbühel-Aggsbach	Umeå	Borlänge
Financial	**Limited** Accessible funding; difficult to improve; national restrictions	**Moderate** Need to push forward; need for capacity building	**Moderate** Available funds; impactful business model; need for focus on barriers	**Moderate** Accessible funding; unimportant financial equity and accessibility	**Moderate** Good means to access funding; need for reinvestment plans
Managerial	**Limited** Established relationships, not sustained capacities; serious impact on trust	**Moderate** Well served; no measures to capacity building and training	**Moderate** Local establishment; need for support, elaboration, and development	**Moderate** Well established; need for review and reflection; less developed capacity building and training	**Moderate** Well established and equipped; need for reflection and brainstorming

Karşıyaka in Türkiye (see Figure 1). The districts were selected as representative pilot sites within the PED-ACT project due to their diverse climatic, cultural, architectural features, and governance contexts, providing a rich basis for comparative analysis of PED development within existing built environments.

3 Case study context

3.1 Austrian context—energy communities in Schönbühel-Aggsbach

In Austria, the 2021 legal reforms accelerated the establishment of energy communities. Despite the legislative push, challenges persist, including administrative complexity, financial limitations, and technical hurdles that have slowed progress. Nonetheless, energy communities have begun to emerge, offering a new approach to localised energy production and governance. A notable example is the energy community in Schönbühel-Aggsbach (Table 4), a rural NGO-driven initiative in Lower Austria (Nasya et al., 2024). The district's current energy demand is approximately 21,200 MWh annually, of which only 25% is currently being met via renewable sources. Reaching Austria's 2050 sustainability targets will require the area to halve its energy demand while fully transitioning to renewables (Nasya et al., 2024).

Due to restrictions on wind and hydro energy solutions in the region, solar power emerges as the primary renewable option, albeit with certain limitations. The Schönbühel-Aggsbach community envisions a just governance and business model that empowers local residents to share affordable, locally produced renewable energy while supporting broader environmental and cultural projects (Stevens, 2024). By emphasising regional collaboration that transcends municipal boundaries, the community aims to build a robust bottom-up framework for PED development. This includes experimenting with financial and funding instruments tailored to the needs of small municipalities. The Schönbühel-Aggsbach case illustrates both the promise and complexity of local energy communities in Austria, highlighting the need for stronger support mechanisms to overcome systemic barriers and enable meaningful contributions to national climate goals.

3.2 Swedish context—urban PED ambitions in Borlänge and Umeå

In Sweden, the transition to Positive Energy Districts hinges on overcoming the considerable energy demands posed by urban environments and cold Nordic climates. Building retrofits play a central role in meeting PED targets, yet the path is complex due to legal, financial, and infrastructural constraints. One such barrier is the limitation on energy sharing between buildings under current Swedish electricity legislation, which prohibits network concessionaires from transferring electricity across property boundaries (Fastighetsägarna, 2022). These challenges are compounded by the need for inclusive participation, as current frameworks often exclude tenants and local residents from decision-making in PED development (Bruck et al., 2022; Nair et al., 2024; Shah et al., 2024).

The municipalities of Borlänge and Umeå (see Table 4) serve as illustrative case studies. Both cities are part of Sweden's Viable Cities initiative and have adopted climate strategies, aiming for climate neutrality by 2030 (CCC) across key sectors such as buildings, transportation, and district heating (excluding industrial energy) (Shah et al., 2024). To achieve these goals, local authorities emphasise energy-efficient retrofits, low-carbon urban planning, and integrated renewable energy solutions. However, success depends on fostering collaborative models that engage residents and stakeholders more directly. In response, initiatives within the Viable Cities program promote participatory governance and strategic partnerships (Nair et al., 2024; Shah et al., 2024). The Swedish context thus underscores the need for legal reform, user inclusion, and multi-stakeholder engagement to achieve scalable and equitable PEDs.

TABLE 4 Overview of case districts.

Topic/Case area	Austria (Schönbühel-Aggsbach)	Sweden (Borlänge & Umeå)	Türkiye (Ankara & Karşıyaka)
Climate context	Rural; moderate, continental climate	Urban; cold, sub-arctic climate	Urban; warm, Mediterranean climate
Legal/policy framework	2021 law enabling energy communities	Viable Cities initiative; legal constraints on energy sharing	SECAPs; Covenant of Mayors; centralised governance
Main renewable focus	Solar (wind/water restricted)	District heating, solar, and retrofits	Solar, geothermal, wind, and hydro potential
Building typology	Mixed rural buildings	Dense urban residential and mixed-use	Low-rise homes (Ankara); dense multi-family buildings (Karşıyaka)
Key barriers	Administrative, financial, technical	Legal constraints lack of user involvement	Centralised authority; property and funding issues
Stakeholde zr participation	Community-led NGO	Municipal-led, limited tenant involvement	University and municipality partnership with co-design intentions
Governance model	Bottom-up; regional collaboration	Top-down with pilot participatory efforts	Top-down with research objectives and co-creation aims
Vision/goal	Shared renewables + cross-financing for local projects	Climate neutrality by 2030 + inclusive PEDs	Reduce demand + on-site renewables; carbon neutrality
International alignment	National law, local innovation	EU-aligned through Viable Cities	EU-linked through SECAP and NetZeroCities
Notable initiative	Bürger*InnenkraftWerk	Viable Cities, retrofitting strategy	SECAP; city climate contract (Karşıyaka)

3.3 Turkish context—climate action in Ankara and Karşıyaka

Türkiye presents a unique context for Positive Energy District development, combining abundant renewable resources with complex governance and socio-economic barriers. While the Mediterranean climate offers high potential for solar, wind, hydro, and geothermal energy, centralised governance, fragmented property ownership, and limited municipal autonomy pose obstacles to decentralised energy solutions. Moreover, financial constraints continue to limit local investments, although public awareness of energy poverty (rooted in the country's experience during the 1980s and 1990s) has generated strong grassroots support for energy transition efforts.

The pilot districts of Ankara and Karşıyaka (metropolitan area of İzmir) (Table 4) provide contrasting yet complementary insights. The Ankara site includes 55 low-rise, single-family homes built in the 1980s (METU, 2024). The city is a signatory of the Covenant of Mayors and has developed a Sustainable Energy and Climate Action Plan (SECAP), focusing on reducing emissions through building retrofits, the promotion of electric vehicles, and investments in public transportation. In Karşıyaka, a 1993-built residential area of 21 buildings as affordable housing is undergoing an energy transition centred on rooftop solar installations and renewable integration in nearby municipal facilities. As part of the NetZeroCities initiative, Karşıyaka signed a City Climate Contract in 2024 to reach carbon neutrality by 2030. Its SECAP includes 32 targeted actions, prioritising solar and geothermal energy and stakeholder engagement.

The overarching objectives in both Turkish cases are twofold: to reduce energy demand in existing buildings and to meet that demand through on-site renewable energy production. Local co-design processes are crucial to foster awareness and sustain long-term transitions. While structural barriers persist, the alignment of local initiatives with EU programs and international funding presents a strategic path forward. The Ankara and Karşıyaka districts exemplify how participatory energy design in PEDs can emerge in non-EU settings when driven by robust municipal leadership and community engagement.

Table 4 shows the main similarities and distinctions of the selected case districts across Austria, Sweden, and Türkiye. While all three case nations aim for climate neutrality (to different extents) and emphasise the integration of renewable energy, their governance models and stakeholder involvement vary significantly. The Austrian case adopts the bottom-up community model, Sweden's cases are municipality-led co-creation initiatives, and municipality-academia-driven test beds form the basis of cooperation in Türkiye. Common challenges include legal constraints, funding challenges, and technical hurdles, yet each context leverages EU-aligned strategies to advance climate neutrality goals, which are ingrained in the PED objectives.

4 Results

Using the evaluation method described in Section 3, the detailed scores for the five cases are summed up, and the reasoning for the score is indicated in keyword descriptions in Table 3. The eight criteria (see Table 1) derived from the PED Matrix serve as different tasks in the PED co-creation. The complexity of the tasks already indicates that a thoroughly elaborated collaboration between different local actors is needed. Addressing social aspects is instrumental in fostering trust within the community. This is a lengthy process and needs to be advanced with the social consent of all actors. Shared values and tangible benefits (e.g., affordable energy for low-income households) can cultivate social consent and support for the project. Providing process support ensures the successful implementation of PEDs, with a view to minimising risks and maximising synergies. While the pivotal function of technical proficiency in the establishment of PEDs

emphasises the necessity for a balanced approach that incorporates local context, innovation, and sustainability, it is governance structures that determine decision-making processes, power distribution, and roles and responsibilities. All these details are critical for the long-term success and sustainability of PEDs. The necessity of environmental consideration in PED projects, with an emphasis on harmonising local, regional, and national priorities within the framework of legal and regulatory constraints, is of great importance. Some of the environmental challenges in PEDs stem from legal and regulatory constraints. Projects are obligated to adhere to heritage laws, environmental regulations, and other legal requirements, which may impose limitations on the deployment of specific technologies (e.g., solar panels or wind turbines) in designated locations. While financial challenges and opportunities in PED projects emphasise the need for stability and long-term planning to ensure the success of energy transitions, effective organisation in PED projects needs continuous management to balance energy production and consumption and to oversee maintenance and adaptations.

4.1 Social aspects

The self-evaluation format reviews cases based on their capacity for social inclusion, identification of social barriers, social interaction, integration of cultural identity, as well as integration of social vulnerability topics into the project. This refers to the social inclusion of citizens through active participation; preserving the heritage, memory, and identity; and fair distribution of the values of the project addressing challenges such as energy poverty (see Table 2).

The scoring of the social aspects for five PED-ACT cases ranged between 4.2–10.0 points (see Table 3). The Austrian case stands out for its strong citizen collaboration, while Borlänge and Umeå score highly due to the structured engagement strategies of the municipalities and the related institutions. Ankara shows moderate potential through private housing management, whereas Karşıyaka faces limitations linked to scale and socio-economic diversity (financially vulnerable residents in a social housing complex). The community in the Austrian case, with an established citizen collaboration, emerges as a viable candidate to advance a citizen-centric PED development; the case has decent replication capacity in similar village structures that are spread widely over an area. Borlänge and the Umeå case display a strong administrative focus on citizen-engagement, obtaining a high ranking among the scored potential PED cases. Given the Turkish context, the Ankara case appears to theoretically have better chances because the housing settlement has a residents' management group, and the socio-economic situation of the residents is better. They also boast an established residents' collaboration, in contrast to the Izmir case, which, due to the size of the buildings and socio-economic differences, has lower capacity when it comes to addressing social aspects. On the flip side, the municipality (external support) interacts and engages with the residents due to the vulnerabilities they are facing in the Izmir case. To summarise, the Ankara case has limited capacities to handle various social aspects, while Izmir, Borlänge and Umeå have moderate capacities, and the citizen-driven energy community in Austria exhibits comprehensive capacities and practices.

4.2 Process aspects

The Positive Energy District (PED) process is a lengthy one, especially in already built and inhabited environments (see Table 2). Relevant criteria in such a process are the clarity and availability of process information, assessment of project phases, data, evaluation, monitoring, accessibility to contacts, and the capacity to react to new or unforeseen situations. The scoring range for the process aspect is lower, falling between 3.2 and 9.2 points for the assessed pilots. As per the scores, Umeå seems to possess relatively better capacity to lead such a PED process towards implementation, while the cases in Ankara, Borlänge, and Austria possess limited capacities, underlining the fact that they need capacity building and training to handle a PED process (see Table 3). The difference between the cases may also be influenced by the experience of site-owners. In the Umeå case, the municipality housing company possessed previous experience in extensive energy efficiency improvement in the buildings near the study area. Hence, they are knowledgeable about the process aspects, including the obstacles, potential achievements, and return-on-investment capabilities. The uncertainties and unclarified responsibilities of identified partners in the Izmir case present a rather substantial obstacle, creating a need for further partner(s) to advance in a PED process. All in all, the social housing pilot in the Izmir area has limited capacity to steer the PED process, while the other pilots have more moderate capacity.

4.3 Technical aspects

Energy transitioning requires technical knowledge and infrastructure. PED developers need technical expertise in the built environment, energy systems, materials, sustainability, building stock, infrastructure, and digitalisation. Citizens, on the other hand, need technical support on the intricacies of building details or the management of heritage requirements. Table 2 presents the key technical dimensions of PED implementation, emphasising alignment between local needs, available technologies, and innovation capacity. The aim is to ensure appropriate technical support and solutions that reflect both user needs and system capabilities.

Technical shortcomings are flagged as critical risks that can hinder the PED performance. The assessed pilots obtained scores ranging from 0.8 to 9.2 points (Table 3) in technical aspects related to becoming a PED. The Swedish city-partnerships have developed excellent technical expertise, which could be beneficial in the development of PED cases in their context. What's more, the Ankara case exhibits some capacity, which could be exploited and improved for a PED implementation. The technical expertise in the Austrian case is rather basic since it is a citizen group. Their structure works well for the energy community, and the partnership would need technical assistance to advance their energy community to a PED, preferably with support coming from unbiased partners such as knowledge hubs or academic partners. The lowest score in terms of technical aspects was found in the Izmir case, which needs a new partnership structure to handle such a complex concept and obtain decisive power on the energy infrastructure. In the Ankara, Borlänge, and Umeå cases, the pilots benefit from the connections and collaboration with the universities—technological solutions are rather close to them through partnerships, resulting in moderate capacities in technological aspects in contrast with the Izmir pilot and the Austrian with their rather limited capacities.

4.4 Governance aspects

Governance models must evolve alongside the PED process to manage increasing complexity, emerging structures, and dependencies, and to uphold inclusivity as a core project value. For instance, the co-governance of citizens and public authorities can signal a balanced power structure. If residents decide on energy pricing, such as electricity costs and investments in their area, they will prioritise their own interests, which in turn may encourage them to develop a more active collaboration. A robust governance scheme is essential for the success of PED projects, ensuring clarity, inclusivity, and resilience. By engaging in the co-development of governance models with local stakeholders and cultivating a collaborative culture, PEDs can achieve long-term sustainability and community ownership. For the governance of a PED, the governance structure and its contribution to the common good, as well as transparency and alignment with other strategies, are very important. Additionally, more, having measures for faulty governing sets the boundaries. Governance aspects for the five pilot cases had scores ranging between 5 and 7.2 points (Karşıyaka was assessed on the border from limited to moderate; all other cases are seen moderate), which indicates that the cases are strongly impacted by context frameworks, the governance structures they are embedded in (which reaches beyond the pilot teams), and the fact that they are not very favourable in any of the cases—perhaps because PED is a relatively new concept. In three of the five detail categories, Umeå has good scores, which once more underlines the capacities of the local partnership. Yet the governance structure and the contribution to the common good in existing neighbourhoods have not materialised so far, and the case is thus rated with 0 points for those criteria. This is why the municipality shares the same governance capacity scoring as Borlänge in Sweden and the Austrian case. The governance capacities in the Turkish case exist but need further development. In the case of Izmir, no institutional measures have been established to address deficiencies in governance, necessitating either the formation of new partnerships or the development of an amended legal framework to implement such corrective mechanisms. Despite the nuances of differences in all pilots, the local structures and frameworks have a moderate capacity to govern PED development.

4.5 Environmental aspects

Project success could be jeopardised by resistance to environmental agendas, legal conflicts, as well as disagreements on what constitutes the borders and boundaries of individual rights and freedoms. Projects may require changes in individual behaviour, such as reducing energy consumption or participating in local energy production, which can sometimes conflict with personal freedoms. Well-organised energy projects can contribute to broader environmental goals, such as species protection, re-naturalisation of areas, the implementation of Nature-Based Solutions (NBS), and circular economy models. The aim in this context will lead to optimised energy and resource consumption (Table 2) and match it with local and sustainable production. The early and transparent addressing of environmental aspects may enable PED projects to achieve sustainable energy consumption and contribute to broader environmental goals. This approach ensures that PEDs are not only technically and economically viable, but also environmentally responsible and socially accepted. Important criteria for the environmental aspect are resource consumption, measure to reduce carbon emissions, circular economy practices, sustainable mobility, and the integration of biodiversity. As cities with a declared commitment to climate neutrality, the Swedish cases bring strong propositions to the environmental criteria. Even though the Austrian case is located in a rural context with very limited possibilities, it has also obtained a good score on environmental topics, which the community can build upon. The topic of mobility remains an issue that could use a significant re-development effort and potentially new partnerships. While the Turkish cases have established certain criteria for environmental protection, they require substantial capacity building across most detailed indicators, particularly in the domains of mobility and biodiversity, where enhanced and expanded partnerships are necessary. The assessed cases score ranges widely between 1.7 and 11.7 points (Table 3), which signals greater differences in how environmental topics are prioritised. We can conclude that the environmental aspects can be handled through a limited scope in the Turkish pilots, moderate in the Austrian case, and comprehensive in the Swedish pilots.

4.6 Legal aspects

The main legal challenges of PED projects result from regulatory challenges. PED projects must operate within a legal framework, energy sharing regulations, data privacy laws (e.g., GDPR), financing conditions, and security requirements. Changing laws, especially those affecting energy exchange or storage, require constant regulatory adaptation. The energy sector's transition challenges traditional legal structures, requiring innovative legal solutions to support new models like PEDs. In legal terms, the developed project needs to comply with laws and regulations, building codes, and citizen data privacy—issues that have not all been fully introduced into the PED concept. Although small-scale, community-driven energy projects are transforming the sector, they often encounter legal loopholes and regulatory uncertainties that can jeopardise their stability and success (see Table 2). This also means that the pilot cases need access to legally proven solutions and develop capacities to resolve legal barriers. The Izmir municipal and academic partnership has no agency to resolve legal barriers, and all other cases have established some legal framework that works better in some areas than in others, which is why they have received a similar score. The Umeå case scores better than the other cases given that those responsible have expertise in laws and regulations, access to proven solutions and experience, and are well-informed on related issues. The assessed cases score in a considerably wide range between 4.2 and 10.8 points (see Table 3), meaning they are well grounded in legal terms, but perhaps need new capacities to enhance PED concepts. The case in Izmir has resulted in the self-evaluation with limited capacities in the collaboration, while the cases from Ankara, Austria, and Borlänge have moderate capacities. Only the Umeå pilot seems to have comprehensive capacities in legal aspects to handle the PED development.

4.7 Financial aspects

The examined PED projects rely on funding and subsidies as part of the European Union's goals towards carbon neutrality. To maximise impact, EU projects should ensure that financial resources benefit the community, which indirectly finances the projects through paid taxes. A comprehensive financial plan needs to encompass investment costs, maintenance, and reinvestment. Projects must elucidate funding sources to ensure financial stability and independence. PED projects (including the developed and assessed cases in this study) often rely on the financial viability of the case and may be one of the biggest obstacles to resolve. In this regard, access to funding, the resolution of financial barriers, financial equity and accessibility, the sustainability of the business model, as well as the reinvestment plan of the project are important criteria. In the context of the Umeå partnership, the financial equity and accessibility could not be rated, which leads to it having a similar score to the Ankara case, which is owned by individual and private homeowners. In the Izmir case, the equity and accessibility, as well as reinvestment plans, are nonexistent. Other than those criteria, all cases have an established financial scheme and limited capacities to handle a PED development project with a range of 2.5 to 7.4 points (Table 3, with limited to moderate capacities in the financial aspects), which signals smaller differences but high dependency on financial opportunities. With some support and capacity building, PED options could be developed. The Austrian case, thanks to the available funding in Austria for energy communities, has access to funding possibilities in the form of PV and electric vehicle subsidies, which could benefit the PED development significantly. Aside from the Izmir case with its limited financial capacities, all pilots estimate their ability to handle financial aspects to be moderate.

4.8 Managerial aspects

The Ankara pilot is managed by a residents' committee that lacks an established structure for capacity building or training. In the Izmir case, management is not carried out by a legal entity, making it more difficult to organise and reform managerial tasks to handle a PED project. In contrast, the Umeå case benefits from a local managing entity (a housing company) that is capable of overseeing energy transition-related tasks, resulting in the highest score among the cases in this comparison. In the Austria, Ankara, and Borlänge cases, the pilots demonstrate similar capacities for managing an energy transition project over the long term, although some training would be necessary to strengthen their managerial capabilities. In the Izmir case, there is a clear need to enhance partnerships so that managerial tasks can be addressed more effectively. The assessed cases scored between 2.5 and 8.3 points (Table 3), highlighting the need to establish or reinforce managerial capacities across the cases.

The management of the PED site can be undertaken by resident associations, as in the case of the Ankara pilot, or energy communities, as in the Austrian pilot, with the integration of social and governance aspects. Nevertheless, managing PED projects requires expertise in areas such as the built environment, energy systems, materials, and digitalisation. In cases where the core team lacks these competencies, obtaining reliable external support becomes essential to fill those gaps. All pilots—except Izmir, which faces specific limitations—possess moderate capacity to manage a PED project during and after implementation through their local structures (such as local owners, management groups, or legal entities).

4.9 Lessons learned

The self-assessment scoring system was used by local project teams in the five pilots to self-evaluate the capacities and possibilities, depending on how established the framework, strategies, focus, objectives, etc. were in relation to the eight aspects. This is a particular self-assessment, with scoring conducted by the present team members in a particular time frame and only related to the assessed pilot case. For other cases, other areas of the same municipality or region, or even other time periods, the scoring may give different results. For instance, the Austrian case has relatively high scores in financial aspects, which were based on the support given to energy communities in Austria at that time. The 2025 government of Austria announced cuts in funds for energy transition, which may change the financial re-scoring results in the future. Similarly, the housing companies in Sweden may have other sites that can achieve a higher score, and the new constellation in Izmir (Izmir's CCC has been endorsed by the EU in 2024) may have new capacities to support PED development. The scoring also does not say anything about the work quality, e.g., how the established entity does the governance, management, or social inclusion. The scoring (Table 3) only assesses if the framework is available in the pilot to be reworked, advanced, or improved. With an existing framework, we mainly require capacity building and improvement. A non-existing framework (score 0) would need to establish the frameworks, which might consume more time and effort, yet would not be an impossible task nor a worse starting point for the PED development.

Comparisons of the five cases show differences and indicate the specific strategies that can be prioritised to enable non-technical as well as technical advancements, as shown in Table 3. For example, Borlänge displays significant variations across the eight aspects (5–11.7). The city has obtained a relatively high score in the environmental aspects, yet the legal aspects need review and elaboration. On the other hand, the Ankara case demonstrates small score variations (4.2–6.7), which could provide valuable evidence for the case's features and the city's consistent approach to urban development and energy transition. For example, both Umeå and Borlänge have valuable technical solutions that can help guide İzmir in creating an investment plan. On the other hand, Austria, Umeå, and Borlänge scored similarly and could share their governance structures and exchange experiences to further enhance resilience.

5 Discussion

In the context of the current energy crisis, it is vital that developments create synergies and involve citizens in the transition process from the beginning. This study demonstrates how territorial capacity building can be fostered by convening diverse groups of stakeholders. Engaging them in the formulation of a unified PED Matrix to help develop the PED roadmap and assigning explicit roles and pathways for all participants is crucial. The stakeholders of future

PEDs can be anticipated to benefit from the cohesive PED approach (see Figure 1) and the systemic analysis of all relevant aspects.

This study serves as a self-reflection step for the planning of capacity building for the PED development. However, the analysis is based on a limited number of respondents, which could have introduced subjectivity and bias into the results. This is because partners and teams were self-evaluating and assessing their respective cases in this project. Hence, the scoring presented in Table 3 is only indicative, and the scoring system should be enhanced by including more respondents from different stakeholder categories and at different stages of PEDs.

The approach is notable for its potential for cross-learning, replication, and scaling-up on a regional scale. Given that the development of PEDs with multifaceted contexts has proven to be a significant challenge for the five cases involved in this study, the collaborative working methods, organisational capacities, and the established methodological processes are promising candidates for further replication.

This methodological approach enables municipalities to align their objectives, requirements, and resources with precision (see Table 3). However, we recommend a further elaboration of citizens' roles to clarify the offers for them and to ensure that they have a realistic chance to participate, engage, and perhaps innovate (Nasya and Vurucu, 2024). This needs to be especially anchored in the social, governance, managerial, legal, and financial aspects. The role of citizens needs to be clear before engagement can start, and this can vary from being an active member of the development scenario to a supporter of the transition. Project developers also need to be clear and honest about how much influence citizens will have in the transition process. The process needs to be transparent regarding the gradual system and the rewards that are offered for engagement. In the long run, a lack of incentives for citizens will not ensure long-term engagement, and the reward does not necessarily need to be on a monetary basis.

By leveraging Natural Language Processing (NLP) techniques to extract PED characteristics from unstructured textual data sourced from various PED project websites and reports, this study was able to elaborate on a matrix system that feeds from various PED sources. This approach enabled the analysis of diverse data sets, providing a foundation for understanding PEDs in a structured manner. The PED Matrix is intentionally flexible, evolving with emerging insights, technologies, and practices to remain relevant for ongoing PED analysis and comparison. The development of the multi-criteria matrix (see Figure 1) designed to characterise Positive Energy Districts was utilised to score selected pilot areas with different constellations, capacities, ownership structures and frameworks, all stemming from built residential areas with existing residents. The PED Matrix (see Table 1) was refined into eight key dimensions: social, process, technical, governance, environmental, legal, financial, and managerial. These dimensions provide a comprehensive framework for mapping and characterising PED projects, facilitating comparison, benchmarking, and information matching across different case cities (see Table 2), which was tested in the PED-ACT pilot cases. The self-scoring system allows the partners of a pilot case to gain an initial overview of which aspects the selected pilot and its partnerships have a good basis to build upon for the energy transition project. Lower-scoring aspects indicate needs for partnership enhancement and capacity building training.

The model developed to characterise and score cases (see Table 4) will need to adapt to new insights, technologies, and practices. As survey data and case studies become more available, the matrix and scoring system will require continuous expansion and adaptation to remain relevant and effective. This will enable a deeper understanding of PEDs and support their development and implementation in alignment with the latest advancements and stakeholder needs. This paper provides insights into the PED-ACT process and will require follow-up actions including further validation and adaptation, feedback from other PED actors, and additional research with specific sets of further cases. The model represents a significant step in creating a structured, multi-criteria framework for characterising PEDs through integrating NLP, public feedback, and expert input.

6 Conclusion

While technology intervention is crucial for PEDs, their future depends on the meaningful and impactful involvement of people and communities in the process, ensuring a holistic and inclusive approach to sustainable urban development and energy transition. The PED Matrix serves as a useful scheme that can help characterise projects and ensure that all aspects relevant to PEDs are included and developed, which will help balance the technical needs and the social ones. The PED Matrix needs to be further expanded to enhance its precision and usefulness with more established PED projects, supporting the development and implementation of PEDs in alignment with the latest advancements and stakeholder needs. We recommend enhancing research on the following topics in future projects: comprehensive analysis, stakeholder engagement, benchmarking and learning, inclusivity, decision-making, systematic replication and scaling, and community-centric solutions.

The presented model can be used by stakeholders such as energy project managers to identify critical areas to focus on, such as energy balance, governance, social inclusion, and financial viability. It supports the integration of non-energy considerations (e.g., cultural heritage, equity, and environmental impact) into PED planning and design. By providing a structured approach, the matrix helps align PED projects with broader sustainability goals and stakeholder expectations. To conclude, the matrix and scoring system can serve as useful tools for advancing inclusive PED development by enabling comprehensive analysis, fostering stakeholder engagement, and supporting informed decision-making. Their use can lead to more diverse, community-focused, and replicable PED solutions, ultimately contributing to the successful implementation of sustainable urban energy transitions.

The methodology employed to use the PED Matrix has proven effective in creating a basis for cross-collaboration, providing a robust tool for analysing and comparing PED projects. Its continuous evolution will ensure it remains a valuable resource for stakeholders involved in energy transition initiatives, balancing technical requirements with community needs and social equity considerations.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants OR patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

BN: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. YV: Conceptualization, Formal analysis, Resources, Writing – original draft, Writing – review & editing. BA: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. DN: Formal analysis, Visualization, Writing – review & editing. GN: Conceptualization, Writing – review & editing. JS: Resources, Writing – original draft. MH: Methodology, Software, Validation, Writing – review & editing. XZ: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2025.1688667/full#supplementary-material

References

Ahlers, D., Driscoll, P., Wibe, H., and Wyckmans, A. (2019). Co-creation of positive energy blocks. *IOP Conf. Ser.: Earth Environ. Sci.* 352:012060. doi: 10.1088/1755-1315/352/1/012060

Ahvenniemi, H., Huovila, A., Pinto-Seppä, I., and Airaksinen, M. (2017). What are the differences between sustainable and smart cities? *Cities* 60, 234–245. doi: 10.1016/j.cities.2016.09.009

Akkaya, B., and Erdoğan, E. (2019). IDEA: Kamusal Ortak Çalışma ve Ortak Üretim Alanı Modeli. Istanbul: Kadıköy Municipality Cultural Publications.

Angelakoglou, K., Kourtzanidis, K., Giourka, P., Apostolopoulos, V., Nikolopoulos, N., and Kantorovitch, J. (2020). From a comprehensive pool to a project-specific list of key performance indicators for monitoring the positive energy transition of smart cities—an experience-based approach. *Smart Cities* 3, 705–735. doi: 10.3390/smartcities3030036

Ansell, C., and Gash, A. (2008). Collaborative governance in theory and practice. *J. Public Adm. Res. Theory* 18, 543–571. doi: 10.1093/jopart/mum032

Arnkil, R., Järvensivu, A., Koski, P., and Piirainen, T. (2014). Exploring the quadruple helix report of quadruple Helix research for the CLIQ project. Available online at: https://files.core.ac.uk/download/pdf/250105751.pdf (Accessed October 08, 2025).

Arnstein, S. R. (1969). A ladder of citizen participation. *J. Am. Inst. Plann.* 35, 216–224. doi: 10.1080/01944366908977225

Baer, D., Loewen, B., Cheng, C., Thomsen, J., Wyckmans, A., Temeljotov-salaj, A., et al. (2021). Approaches to social innovation in Positive Energy Districts (PEDs)—a comparison of Norwegian projects. *Sustainability* 13:7362. doi: 10.3390/SU13137362

Bossi, S., Gollner, C., and Theierling, S. (2020). Towards 100 Positive Energy Districts in Europe: preliminary data analysis of 61 European cases. *Energies* 13:6083. doi: 10.3390/EN13226083

Brozovsky, J., Gustavsen, A., and Gaitani, N. (2021). Zero emission neighbourhoods and Positive Energy Districts—a state-of-the-art review. *Sustain. Cities Soc.* 72:103013. doi: 10.1016/J.SCS.2021.103013

Bruck, A., Diaz Ruano, S., and Auer, H. (2022). Values and implications of building envelope retrofitting for residential Positive Energy Districts. *Energ. Buildings* 275:112493. doi: 10.1016/J.ENBUILD.2022.112493

Bryson, J. M., Crosby, B. C., and Stone, M. M. (2006). The design and implementation of cross-sector collaborations: propositions from the literature. *Public Adm. Rev.* 66, 44–55. doi: 10.1111/j.1540-6210.2006.00665.x

Carayannis, E., and Campbell, D. (2009). "Mode 3" and "Quadruple Helix": toward a 21st century fractal innovation ecosystem. *Int. J. Technol. Manage.* 46:201. doi: 10.1504/IJTM.2009.023374

Clerici Maestosi, P. (2021). Smart cities and Positive Energy Districts: urban perspectives in 2020. *Energies* 14:2351. doi: 10.3390/en14092351

Corsini, F., Certomà, C., Dyer, M., and Frey, M. (2019). Participatory energy: research, imaginaries and practices on people' contribute to energy systems in the smart city. *Technol. Forecast. Soc. Chang.* 142, 322–332. doi: 10.1016/j.techfore.2018.07.028

Ertelt, S.-M., and Carlborg, P. (2024). "Inclusive urban energy futures? Unveiling justice conflicts in the European vision for Positive Energy Districts" in Conflicts in urban future-making: governance, institutions, and transformative change (Bielefeld: Transcript Verlag).

Fastighetsägarna. (2022). Så kan du dela el i lokala nät. Available online at: https://www.fastighetsagarna.se/aktuellt/webbinarier/sa-kan-du-dela-el-i-lokala-nat/. (Accessed September 5, 2022).

Fung, A. (2006). Varieties of participation in complex governance. *Public Adm. Rev.* 66, 66–75. doi: 10.1111/j.1540-6210.2006.00667.x

Fung, A., and Wright, E. O. (2011). Deepening democracy: institutional innovations in empowered participatory governance. London: Verso.

Gupta, K., Zhang, W., and Hall, R. P. (2021). Risk priorities and their co-occurrences in smart city project implementation: evidence from India's Smart Cities Mission (SCM). *Environ. Plan. B* 48, 880–894. doi: 10.1177/2399808320907607

Han, M., Alpagut, B., and Nasya, B. (2024). Multi-criteria matrix for the characterization of existing PEDs.

Han, M., Shah, J., and Zhang, X. (2023). Review of natural language processing techniques for characterizing Positive Energy Districts. *J. Phys.: Conf. Ser.* 2600:082024. doi: 10.1088/1742-6596/2600/8/082024

Hearn, A., Sohre, A., and Burger, P. (2021). Innovative but unjust? Analysing the opportunities and justice issues within Positive Energy Districts in Europe. *Energy Res. Soc. Sci.* 78:102127. doi: 10.1016/j.erss.2021.102127

IEA. (2019). The critical role of buildings: perspectives for the clean energy transition. Available online at: https://www.iea.org/reports/the-critical-role-of-buildings. (Accessed May 24, 2025)

ISO. (2014). How does your city compare to others? New ISO standard to measure up. Available online at: https://www.iso.org/news/2014/05/Ref1848.html. (Accessed October 3, 2025)

Kozlowska, A., Guarino, F., Volpe, R., Bisello, A., Gabaldòn, A., Rezaei, A., et al. (2024). Positive Energy Districts: fundamentals, assessment methodologies, modeling and research gaps. *Energies* 17:4425. doi: 10.3390/en17174425

Krangsås, S. G., Steemers, K., Konstantinou, T., Soutullo, S., Liu, M., Giancola, E., et al. (2021). Positive Energy Districts: identifying challenges and interdependencies. *Sustainability* 13:10551. doi: 10.3390/su131910551

Maestosi, P. C., Andreucci, M. B., and Civiero, P. (2021). Sustainable urban areas for 2030 in a post-COVID-19 scenario: focus on innovative research and funding frameworks to boost transition towards 100 Positive Energy Districts and 100 climate-neutral cities. *Energies* 14:216. doi: 10.3390/EN14010216

Magrini, A., Lentini, G., Cuman, S., Bodrato, A., and Marenco, L. (2020). From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): the next challenge—the most recent European trends with some notes on the energy analysis of a forerunner PEB example. *Dev. Built Environ.* 3:100019. doi: 10.1016/J.DIBE.2020.100019

McKenzie-Mohr, D. (2011). Fostering sustainable behavior: an introduction to community-based social marketing. *3rd* Edn. New York: New Society Publishers.

Merino-Saum, A., Halla, P., Superti, V., Boesch, A., and Binder, C. R. (2020). Indicators for urban sustainability: key lessons from a systematic analysis of 67 measurement initiatives. *Ecol. Indic.* 119:106879. doi: 10.1016/j.ecolind.2020.106879

METU (2024). Positive energy transition in a neighborhood scale: case study in Ankara and İzmir, Türkiye. Schönbühel-Aggsbach: PED-ACT.

Mulgan, G. (2006). The process of social innovation. *Innov. Technol. Gov. Glob.* 1, 145–162. doi: 10.1162/itgg.2006.1.2.145

Nair, G., Mattsson, M., Danielski, I., Nasya, B., and Akkaya, B. (2024). Baseline Study in Ålidhem District in Umeå. Schönbühel-Aggsbach: PED-ACT.

Nasya, B., and Vurucu, Y. (2024). Co-created Positive Energy Districts. 5th Urban Economy Forum + 59th ISOCARP World Planning Congress. 1–5.

Nasya, B., Vurucu, Y., and Akkaya, B. (2024). PED MANIFESTO turning the balance of local energy into positive. Wien: Wonderland.

Nasya, B., Vurucu, Y., Akkaya, B., Blender, M., Horak, D., and Sovantania, K. (2024). Baseline study energy community. Schönbühel-Aggsbach: PED-ACT.

Nguyen, M. T., and Batel, S. (2021). A critical framework to develop human-centric Positive Energy Districts: towards justice, inclusion, and well-being. *Front. Sustain. Cities* 3:691236. doi: 10.3389/FRSC.2021.691236

Olivadese, R., Alpagut, B., Revilla, B. P., Brouwer, J., Georgiadou, V., Woestenburg, A., et al. (2020). Towards energy citizenship for a just and inclusive transition: lessons learned on collaborative approach of Positive Energy Districts from the EU Horizon2020 smart cities and communities projects. *Proceedings* 65:20. doi: 10.3390/PROCEEDINGS2020065020

Orova, M., and Reith, A. (2024). Defining a common set of key performance indicators for Positive Energy Districts. Available online at: https://abud.hu/wp-content/uploads/2024/07/750_FinalPaperSubmission-1.pdf (Accessed October 08, 2025).

Palm, J., and Reindl, K. (2018). Understanding barriers to energy-efficiency renovations of multifamily dwellings. *Energ. Effic.* 11, 53–65. doi: 10.1007/s12053-017-9549-9

Parag, Y., and Sovacool, B. K. (2016). Electricity market design for the prosumer era. *Nat. Energy* 1:16032. doi: 10.1038/nenergy.2016.32

Prahalad, C. K., and Ramaswamy, V. (2004). Co-creation experiences: the next practice in value creation. *J. Interact. Mark.* 18, 5–14. doi: 10.1002/dir.20015

Sanders, E. B.-N., and Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign* 4, 5–18. doi: 10.1080/15710880701875068

Sareen, S., Albert-Seifried, V., Aelenei, L., Reda, F., Etminan, G., Andreucci, M. B., et al. (2022). Ten questions concerning Positive Energy Districts. *Build. Environ.* 216:109017. doi: 10.1016/J.BUILDENV.2022.109017

Sassenou, L.-N., Olivieri, L., and Olivieri, F. (2024). Challenges for Positive Energy Districts deployment: a systematic review. *Renew. Sust. Energ. Rev.* 191:114152. doi: 10.1016/j.rser.2023.114152

Schneider, S. (2023). Definition of Positive Energy Districts. Vienna: University of Applied Sciences Vienna.

Schütz, F., Heidingsfelder, M. L., and Schraudner, M. (2019). Co-shaping the future in quadruple helix innovation systems: uncovering public preferences toward participatory research and innovation. *She Ji: J. Des. Econ. Innov.* 5, 128–146. doi: 10.1016/j.sheji.2019.04.002

Shah, J., Shen, J., Zhang, X., Nasya, B., and Akkaya, B. (2024). Baseline study energy community Jakobsgårdarna area. Schönbühel-Aggsbach: PED-ACT.

Smart Cities Dive. (2025). What are the best indicators for measuring the sustainability of cities?. Available online at: https://www.smartcitiesdive.com/ex/sustainablecitiescollective/what-are-best-indicators-measuring-sustainability-cities/1047756/. (Accessed October 3, 2025)

Sovacool, B. K. (2014). What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Res. Soc. Sci.* 1, 1–29. doi: 10.1016/j.erss.2014.02.003

Sovacool, B. K., Martiskainen, M., Hook, A., and Baker, L. (2019). Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions. *Clim. Change* 155, 581–619. doi: 10.1007/s10584-019-02521-7

Stevens, U. (2024) Bürger*innenKRAFTwerk.

The Arcadis Sustainable Cities Index. (2024). 2,000 days to achieve a sustainable future. Available online at: https://www.arcadis.com/en/insights/perspectives/global/sustainable-cities-index-2024. (Accessed October 3, 2025)

The Green City Index. (n.d.)

Toffler, A. (1980). The third wave. New York, NY: Morrow.

Williams, P. (2002). The competent boundary spanner. *Public Adm.* 80, 103–124. doi: 10.1111/1467-9299.00296

Young, I. M. (2002). Inclusion and democracy. *1st* Edn. Oxford: Oxford University Press.