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Ten questions concerning positive energy districts

Siddharth Sareen [a,*], Vicky Albert-Seifried [b], Laura Aelenei [c], Francesco Reda [d], Ghazal Etminan [e], Maria-Beatrice Andreucci [f], Michal Kuzmic [g], Nienke Maas [h], Oscar Seco [i], Paolo Civiero [j], Savis Gohari [k], Mari Hukkalainen [d], Hans-Martin Neumann [e]

[a] University of Stavanger, Norway
[b] Fraunhofer Institute for Solar Energy Systems ISE, Germany
[c] National Laboratory of Energy and Geology (LNEG), Portugal
[d] VTT Technical Research Centre of Finland Ltd., Finland
[e] Austrian Institute of Technology (AIT), Austria
[f] Sapienza Università di Roma, Italy
[g] Czech Technical University in Prague, Czech Republic
[h] The Netherlands Organisation for Applied Scientific Research (TNO), the Netherlands
[i] Spanish Research Centre for Energy, Environment and Technology (CIEMAT), Spain
[j] Roma Tre University, Italy
[k] Oslo Metropolitan University, Norway

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ABSTRACT

Positive Energy Districts (PEDs) constitute an emerging energy transition paradigm, with an ambitious timeline for rapid upscaling to match the urgency of climate mitigation and adaptation. Increasingly networked and coordinated actors aim to realise 100 PEDs across Europe by 2025. This resonates with the mission orientation turn of the European Green New Deal, to inspire and enable target-driven innovation. Yet it raises questions that have long perplexed scholars and practitioners in energy transitions: how can rapid diffusion be achieved in a sustained and replicable manner in diverse socio-technical contexts? Identifying the key questions to address and implement fit-to-purpose solutions within short-term project timescales is essential in order to mainstream PEDs. Such solutionism must be accompanied by a healthy dose of scepticism, in order to avoid undesirable outcomes such as exacerbated inequalities, societal backlash, and spatial displacement of invisible burdens. But it also requires proactive sharing of experiences, responsive learning and dissemination, and cooperation across sectors and disciplines. In this timely contribution, thirteen researchers from nine European countries flag ten questions concerning PEDs, and offer preliminary responses in line with cutting-edge insights informed by science and practice. This contribution draws on multidisciplinary competence in steering the Positive Energy Districts European Network, and aims to make emerging knowledge widely available, while also inviting constructive critique and engagement within the PED arena which features a broad range of diverse stakeholders. Authors highlight key pathways forward for a rapid, far-reaching translation of the ambitious PEDs agenda into multi-sited, district-scale beacons of sustainable energy transition.

1. Introduction

Setting energy transition targets by moving beyond individual buildings towards a district or neighbourhood scale is a relatively new endeavour in both scientific research and realised projects. Positive Energy Districts (PEDs) have steadily gained importance and recognition on the energy transition policy agenda of the European Commission, as a key part of societal solutions towards low-carbon futures. Several PED concepts exist, but in terms of a legal framework, no formal definition is embedded in European legislation yet [1].

According to the Joint Programming Initiative Urban Europe (JPI Urban Europe), which manages the PED programme on behalf of the European Commission, PEDs are defined as: "Energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and

* Corresponding author.
E-mail address: siddharth.sareen@uis.no (S. Sareen).

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Nomenclature

COST	Cooperation On Science and Technology
Covid-19	novel coronavirus
DSO	distribution service operator
ESCo	energy service companies
ICT	Information and Communication Technologies
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
JPI	Joint Programming Initiative
LEC	local energy communities
PED	positive energy district
PED-EU-NET	Positive Energy Districts European Network
REC	renewable energy communities
R&I	research and innovation
SCC	smart cities and communities
SDG	Sustainable Development Goal
SET	Strategic Energy Technology
UN	United Nations
UNSD	United Nations Statistics Division
WHO	World Health Organization

interaction between buildings, the users and the regional energy, mobility and information and communication technology (ICT) systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability" [2].

As a policy object, they represent a target of 100 functional PEDs across Europe by 2025, and progress had been made by 2020, but with ambitious tasks ahead along a compressed timescale [3]. To date, there are a handful of PEDs in operation and a large number under implementation [2]. This is a crucial piece of the puzzle to achieve the European Commission target of 100 climate-neutral cities by 2030, as the main mandate of the Mission Board for 100 climate-neutral and smart cities [4]. A target of 100 PEDs is simultaneously ambitious and modest: ambitious because of the practical challenges of implementing this across distinct contexts within a short timescale by 2025, and modest because 100 PEDs are but a fraction of the challenge of requisite low-carbon urban transition. A key motive in piloting a range of diverse cases is to furnish a basis to understand scalability and replicability, so as to mainstream PEDs or some of their constitutive elements across a far greater number of contexts shortly thereafter [5], Significant knowledge gaps remain, making the mapping of challenges and learning by doing key aspects of progress on governance, socio-technical and economic issues [6]. Many individual components of PEDs, e.g. pertaining to energy efficiency measures, are not novel in themselves (see e.g. Ref. [7], but their combined deployment and the overarching aim marks a renewed, politically embraced ambition in Europe, at least partly propelled by rapid cost declines in renewable energy sources and sustainable building technologies and materials.

The sub-urban scalar focus of PEDs enables a clear action orientation, focusing attention on policy implementation and the actual attainment of targets in a diverse range of contexts across Europe. Given the urban diversity of the European continent, this programme of innovation and rapid directed change has rich potential to yield urgent transferable insights for cross-fertilisation to a range of contexts worldwide, with distinct geographies and politics, urban forms and metabolisms, and infrastructural legacies. Despite the unique nature of each PED case in terms of conditions of emergence and context, experiences and analyses across a diverse range hold scope for meaningful transferability to other contexts where decision-makers are aware of local specificities and able to adapt information to customised purposes. Thus, PEDs constitute a key initiative towards urban transformation for low-carbon futures, cutting across sectors to show how real-life neighbourhoods and districts can be part of effective climate mitigation solutions.

On a more abstract level, PEDs operate at a territorial scale that has immediacy to European inhabitants. An urban district is where most people reside, thus initiatives at the district scale bring climate change and energy transition mitigation and adaptation into the everyday psyche and experiential reality of inhabitants within a neighbourhood. Public acceptance of necessary actions can be aided by shining, locally desirable examples that attract attention and demonstrate positive impact. PEDs constitute an opportunity to realise the directive on local energy communities (LEC) and renewable energy communities (REC), as they can facilitate the transfer of ownership over and involvement in energy systems to a broad swathe of locally based stakeholders. Such potential commoning of economic benefits through PEDs is one of their key envisaged positive impacts.

A number of dynamics and decisions are involved in the ongoing rollout of PEDs. As thirteen authors from nine European countries, we engage closely with relevant processes, and are involved in coordinating the Positive Energy Districts European Network (PED-EU-NET). In this paper, we draw on collective insights to provide an overview of the key barriers and possibilities for 100 PEDs to be achieved. We complement this with some more general reflections related to the implementation of PEDs. PED-EU-NET spans 38 countries with over 100 members, and runs during 2020–2024 (see https://pedeu.net for a detailed overview). Hence this contribution aims to provide a solid foundation to develop further. In doing so, we are mindful of the existing and ongoing work that has established PEDs as a policy object, notably by the European Energy Research Alliance's Joint Programme Smart Cities, the Joint Programming Initiative Urban Europe's Stakeholder Involvement Platform Agora, the International Energy Agency (IEA) Annex 83 focused on PEDs, and most directly through the European Strategic Energy Technology (SET) Plan Action 3.2 (the 100 Positive Energy Districts Programme).

To strike a balance between details on PEDs specific to the ongoing European initiative, and more broadly oriented reflections that enable transferability of insights to PEDs per se, the paper is structured in three thematic sections, which we set up in the answer to the first of the ten questions. These sections focus on *framework conditions* (the institutional structures and contexts within which PEDs are being rolled out), *prefiguration* (the dynamics of preparing the ground for PEDs to be achieved, notably 100 of them by 2024), and *emerging impact* (insights on implementation from the initiatives underway). We devote three questions and answers per section. Thereafter, a concluding section synthesises insights and offers our collective reflections on the major barriers and possibilities for PEDs to be realised. The answers include select references to scholarly and/or policy sources to direct readers who wish to delve deeper.

2. Ten questions and answers

Q1. What enabling conditions are required to support rapid scaling up of PEDs in Europe?

A1. Enabling conditions to scale PEDs comprise the overarching concern across the other questions, and are addressed in three thematic sections: *(a) Framework conditions, (b) Prefiguration*, and *(c) Emerging impact.*

The creation of 100 PEDs by 2025 requires rapid and large-scale uptake of the concept across Europe. The overarching objective of PED-EU-NET is to drive this development by consolidating a wide existing knowledge base [8] and harnessing the collective power of diverse stakeholders. We split the challenge into three parts: framework conditions, prefiguration, and emerging impact. We seek to address each of them specifically through the collaborative capacity of our network, in concert with the other aforementioned key stakeholders.

Framework conditions are a set of core principles that enable the successful implementation of PEDs. On the technical side, the energy system underlying PEDs is characterised by diverse renewable energy supplies, a high level of energy efficiency and a substantial degree of flexibility. Cities as problem owners in the PED transformation ought to find their own optimal balance between these three pillars [2]. We are mindful of the necessity to empower cities with the knowledge and tools needed to craft their unique pathway to PEDs [9]. Importantly, cities are not alone in this journey. Involvement of other stakeholders – such as regional and national governments, industry actors, research and innovation (R&I) professionals and citizen groups – especially early on, is seen as a defining factor for successful PED development [3]. The institutionalisation of regulatory and legislative enablements is vital in orientating action, encouraging cooperation and helping actors steer a course towards joint implementation of the vast array of activities required to implement any PED.

Prefiguration refers to the preparation needed to ensure a smooth PED process. PED development is a complex process, which requires multiple stakeholders to join forces in pushing forward major urban changes. To facilitate this complex process, a collaborative governance model is imperative to connect different stakeholders and align their interests and priorities [10]. The establishment of a common vision and shared values among stakeholders is key to driving such a collaborative process [11]. Motivating key stakeholders to create a critical mass can help kickstart momentum. We acknowledge the challenge of implementing a collaborative governance process in PED projects; it is thus urgent and important to acquire a deeper understanding of viable methods and tools through empirical testing [12].

Emerging impact refer to the direct and indirect effects associated with PEDs. They can be translated into incentives for mobilising stakeholder participation. The energy-related impacts – namely lower energy consumption, higher energy efficiency, reduced reliance on fossil fuels and increased system flexibility – are direct benefits to multiple stakeholders (including households, local government and power grid operators) [13]. In addition, PED development can bring a wide range of non-energy-related benefits that should not be overlooked. These co-benefits span the environmental, social, health and economic spheres and can potentially offset the additional costs involved in the development of PEDs [14]. The key is to find the synergies and unlock the co-benefits of multiple stakeholders as a way to mobilise support in the PED transformation.

These three thematic sections are intuitively sequential, and their importance depends on the context in which a particular PED development project unfolds, as well as with each level of advance it attains. Considering them can serve as an analytical guide for decision-makers on how to best enable PEDs.

1.1. Framework conditions: Core principles

Q2. What relational components are essential for a city to successfully implement PEDs?
A2. The ability to integrate technical and non-technical capabilities and engage stakeholders within and outside the city hall, complemented by the capacity to learn, are key relational components to success.

The implementation of innovation is not easy, and hardly finds a place among the business-as-usual processes of city halls, energy suppliers, housing associations and other relevant institutions [15]. The energy system technologies and advanced innovative services and business models required for PED implementation are quite complex, and need to be built upon technologies that are in place. Maas et al. [16] used an innovation implementation framework in two lighthouse cities to enhance district scale energy flexibility, and concluded that the organisational capacity of a city is key for successful implementation. This capacity has to deal with the catch that while solutions or ideas close to existing norms are much easier to implement and diffuse, an innovative smart solution could be the perfect solution to a difficult problem but hard to gain traction for [17]. A productive way forward would be for cities to recognise the implementation of smart solutions as part of a wider innovation programme, rather than treating them in line with traditional urban development projects [18]; this requires strong relationships between actors on knowledge, practice and policy [19].

Integrated planning is one coordinating mechanism between several governance layers for spatial development. In all PED lighthouse projects (e.g. SPARCS, Making Cities, Atelier, CityXChange), a key question is how to deliver an integrated city vision. Collaboration between the city hall and external partners is important [20]. Within the city hall, PED projects need to be embedded at operational, tactical and strategic levels, and backed by administrative assurance. Confidence should be created within the citizen community that PED projects are not just technology-driven prestige projects but can really help to create value for citizens, such as through neighbourhood upgrades and cleaner air, while avoiding the reproduction of existing urban disparities [21]. Concepts and methods like the participation ladder [22], open government platforms like WeLive [23], and citizen labs offer several pertinent insights on citizen involvement. Citizen energy communities go beyond involvement and engagement and regard citizens as participants with ownership of the energy system in the PED.

Practical guidelines and concepts also exist for aligning initiatives with stakeholder needs [24,25], for instance based on the mutual gains approach [26]. As Rotmans [20] expounds upon, alignment with cognate district challenges like climate change and accessibility is essential. A holistic approach based on socio-technical systems [27] can generate actionable inputs to integrate technical and non-technical capabilities. The implementation of PEDs constitutes a transition that features many uncertainties in decision-making that actors need to cope with, hence the capacity to learn and adapt is key at both individual and institutional levels [28].

Q3. Which structural aspects are key for the effective implementation of PEDs?
A3. Key structural aspects include urban governance models and institutional architecture that can ensure effective implementation, based on research and innovation, pilot projects, and strategic capacity-building.

Any conceptual framework that undergirds PEDs requires a holistic integrated approach where technological, social, economic, financial and regulatory aspects should be addressed to successfully implement an urban sustainable energy transition [13]. It is generally agreed that PEDs require a well-designed process based on different development phases. These include integrative energy planning, effective PED implementation and monitoring, strategic capacity-building, and key stakeholder involvement starting from the initial stages of PED processes and extending throughout all its phases.

For this reason, a key aspect is an urban governance framework for PEDs, built upon a strong partnership between several stakeholders, namely collaborative governance. This collaborative governance must enable the sharing of knowledge and experiences from a wide range of sectors and fields: research, industry, public administration, financial, economic and social. The model of collaborative governance has been extensively studied and elaborated [29]. Theoretically, the collaborative governance model is often associated with cities or districts, wherein governance combines two concepts [30]. The first – *collaboration* – refers to cooperation premised on recognition of the value of reciprocity to achieve common goals, working across boundaries in multi-sector relationships. The second – *governance* – concerns steering the process that influences decisions and actions within the public, private, academic and civic sectors.

In the context of PED deployment and implementation, collaborative governance can help ensure a strategic programme accompanied by opportunities for collaboration and networking between and across different actors [31]. Such synergistic, orientated networking is based on applied research including strategic innovation, innovative technological solutions, demonstration projects, urban innovation laboratories (experimental platforms), and on local capacity building that takes into account all relevant technological (energy efficiency, renewable integration, energy system flexibility) and non-technological (social, environmental, economic) aspects [32].

Moreover, from an operational point of view, urban collaborative governance should be based on an effective operational structure in order to ensure open dialogue [33], and a consultative process with adequate consideration of stakeholders' interests and priorities, a transparent membership/cooperation protocol, and smooth, effective communication between partners and a wider set of stakeholders. This is closely related to the relational components in Q2. Collaborative governance insights can thus provide an open framework where the core stakeholders not only join forces in accordance with their specific interests, but thereby create a common programme for PEDs and cities.

Q4. What engagement strategies in PED implementation can ensure fruitful co-creation processes?
A4. Early engagement among key technical and non-technical stakeholders who feel ownership can help develop successful co-creation strategies throughout integrated design and implementation phases.

It is important to identify the key stakeholders needed in the development and implementation of a PED from the very start of the planning project, and to create the conditions to invite them on board with a sense of co-ownership of the process and outcome. The land and property owners need to be included early, to clarify the benefits, requirements and impacts of the PED project; yet there is little research on PEDs in this regard to date. Similarly, local energy system operators and local energy producers for both electricity network and district heating and cooling have to be involved at an early stage to assess local conditions for implementation of advanced functionalities that can enable energy transactions between peers [34]. In addition, local actors who can develop capabilities for energy balancing and aggregation of loads and renewable energy source generators should be included (e.g. energy community entities, energy service companies (ESCos), property owners and managers, and energy storage system operators) [35].

Urban planners need to be supported for compliance with PED requirements, as do practitioners such as energy companies, transport operators and logistics providers. Here, national agencies (such as for energy efficiency and climate action) can play vital catalysing roles by ensuring translation of evolving regulations into actionable guidelines for local implementation in these actors' protocols and in sync with each other across different governance levels. The role of intermediaries is gaining recognition in transition literature on district energy planning [36]. At the local scale, collaboration between different departments within municipalities needs to ensure that all relevant technical and non-technical aspects are considered in the planning process, and that the project is aligned with long-term urban development strategies [37]. Importantly, residents, employees and other citizens should be brought on board during the planning phase for inputs prior to communication of proposed plans, for which many promising models exist, such as citizen assemblies and participatory budgeting [38,39].

The questions related to the ownership and management of systems, and also relating to the governance of PED energy flows, need to be discussed and addressed among the key partners. Here, local differences play a significant role: who owns the land and whether the site is an existing urban environment or a greenfield development [40]. If changes are needed to the master plan, then the requirements for PEDs should be identified and clarified with urban planners, with mapping of the local possibilities to implement a variety of PED solutions. Here, the expertise of and consultation with researchers and technical experts is essential to assess contextually informed socio-technical prerequisites, undertake a preliminary design of feasible technical solutions, and accompany their refinement and deployment in order to shape them on an ongoing basis that is responsive to the needs of diverse users and publics [41] without jeopardizing PED ambitions. Such a holistic process can be complemented by parallel consultations with aforementioned stakeholders, creating arenas for feedback and building reflexivity into the process. The development of energy communities can also plausibly be linked with PED development, where it is key to convince developers about the brand value of the PED standard in order to bring them on board.

1.2. Prefiguration: Preparing the ground

Q5. What collaborative governance processes and functionalities undergird PEDs?
A5. Collaborative governance processes require a range of methodological tools and competencies to enable tailored engagement amongst diverse stakeholders with clearly allocated roles and responsibilities.

Scholars have convincingly argued that the success of energy transitions depends greatly on collaborative governance [42–44]. The term stresses heterarchical forms (integrated top-down and bottom-up processes) of reflexive self-organisation with informal interpersonal networks and inter-organisational relations [45]. A variety of empirical case studies have shown that the plurality of interests and strategies of collaborative governance has held back energy transitions to various extents and in diverse ways [42–44]. While the intrinsic motivation of individual stakeholders may be high, hardly any exchange of information and knowledge takes place in many contexts, hindered by fluid regulatory and legislative bases that introduce uncertainty rather than creating a framework for structured cooperation. In addition, the involved actors lack an overarching common strategy, because each one seeks to fulfil a very specific agenda. Thus, stakeholders remain siloed in their own organisational environment and only collaborate through narrowly defined and established networks [44].

Thus, even though actors and scholars acknowledge the necessity of collaborative governance, empirical analyses raise questions about the legitimacy and accountability of informal networks, compared to the formal mechanisms. How can forms of partnership engender cooperation among actors in ways that align priorities over time and institutionalise collaborative governance? Research suggests that the more organisations participate in collaborative decision-making processes, the more time-consuming and resource-intensive such processes tend to become [43,44]. The orientation of planning and decision-making processes, the rules of the game (institutional structures) and strategic tactics continue to co-evolve. Thus, an in-depth understanding of complex and dynamic governance systems for PEDs requires a temporal, iterative and interactive approach as well as political, cultural and periodic review.

Insights exist on how institutional conditions, power struggles, the roles of individuals, and socio-material contexts shape technological and policy interventions, and in turn influence energy governance [43]. While empirical studies of urban energy governance are emergent, it is fair to say that the governance of PEDs currently suffers from a relative lack of cohesive conceptual and methodological understanding [42]. Thus, bringing scholarly insights into play in the design and conduct of emerging PED implementation arenas is a key priority to enable collaborative governance. Here, scholarship on collaborative business models can provide some cues, for instance tools adapted to smart city contexts (see e.g. Ref. [46] and towards nurturing alliances (see e.g. Ref. [47], as can conceptual contributions on policy-oriented strategic alignment and mobilisation [48].

Q6. What would prototype design patterns for PEDs look like?

A6. While examples of design patterns for PEDs are beginning to proliferate, they require systematic prototyping and contextualisation to diverse urban forms and socio-cultural settings.

As a core point of departure, PED design is premised on the 'no standard' rule, in recognition of the fact that context matters; for instance whether the development in question is a retrofit or a new construction. Rapid evolution in technologies for energy efficiency and renewable energy integration in buildings necessitates a research-to-design approach, for instance in relation to new modes of integrating energy flexibility to balance supply and demand more locally and with benefit sharing among residents [49]. The socio-technical innovation that accompanies such an approach implies a need to experiment with and validate the feasibility of co-produced PED designs for distinct components and diverse configurations [6]. Such assessment and adaptive monitoring of design solutions presents a complex challenge in itself, on the one hand enabling high customisation and flexibility while on the other hand posing difficulties of transparency and transferability that must be dealt with for solutions to be scalable across contexts. A natural check mechanism is that to live up to a PED definition, the development in question must be net energy positive, producing more energy than it consumes, which is itself a novel challenge to measure and monitor at the district scale [50].

Over time, diverse contexts, patterns in urban form, building typologies and climatic zones will yield nuanced typologies of PEDs. For instance, districts in Southern Europe are likely to make more use of their high solar irradiation rates by rapidly installing solar photovoltaic panels on roofs and facades, and can be developed on a building-by-building or block-by-block basis, but this will necessitate considerable seasonal and daily energy storage to achieve autonomous PEDs due to flux in solar generation [51]. By contrast, Western European contexts like The Netherlands have many options for aquathermal and geothermal sources, which lower the need for seasonal heat storage, but require more collective systems with high up-front capital investment; this entails higher initial financial risk and makes rapid connections across blocks and professionalised collective organising more likely [52].

Overall, prototyping will serve an important function over time, to enable the scaling of PEDs and ease the process of identifying which design patterns and energy system configurations are likely to match user needs in a specific district. This is consistent with the attention to technology readiness levels in European Commission project grants across the spectrum of technical maturity, from ideation and testing to piloting and scaling towards state-of-the-art design solutions. Such prototyping of PEDs must necessarily embody a co-creation approach where iterative citizen engagement with scope to exercise agency builds in reflexivity and ensures socio-technical prototypes with greater likelihood of real-world deployability in line with their envisaged purpose. Prototypes are also essential for enabling assessment by financiers from banks as well as local and national governments [53]. Importantly, prototyping can enhance trust by local home-owners and inhabitants of the districts in question, by providing evidence that the chosen design is really the state-of-the-art and fit-for-purpose. At present, however, the trial-and-error stage of development outside the regulatory sandbox, where PEDs are moving beyond experimentation to implementing various combinations of technologies [54], implies that it is important to take graduated steps into prototyping, while maintaining a broad outlook that is proactively open to innovation.

Q7. How can diverse stakeholders create a critical mass to implement PED?
A7. PEDs do not originate on their own, but rather, require systematic facilitation geared towards kickstarting local PED ecosystems and developing political constituencies and clusters of expertise.

In practice, the lack of a 'city-administration and cross-sectoral approach' coupled with 'stakeholder involvement' comprises the most commonly encountered barrier for PED projects analysed by JPI Urban Europe [3]. The initial motivation of stakeholders is an underlying factor for any successful PED. In this regard, the increased complexity of the PED concept – relative to building level concepts – complicates rapid uptake and replication of PEDs across Europe. The family of Smart Cities and Communities (SCC) lighthouse projects has been systematically working towards overcoming the barriers both at the individual and city hall level. Lessons learned from the SCC projects point to the central role played by motivated key stakeholders, who represent the critical mass for any given PED project.

The initial proposition to implement PED is often developed by an individual or organisation that plays the facilitator role. The facilitator acts as a catalyst, first ensuring an understanding of the PED concept by the key stakeholders, and then activating these stakeholders by helping them to frame their motivation and identify available incentives. This is also key to avoiding PEDs becoming a vehicle for eco-gentrification [55]. In most of the SCC projects studied, the creation of some form of public-private partnership was instrumental to enabling the PED. From the facilitator's perspective, the motivation for each type of key stakeholder needs to be clearly articulated in terms of benefits at the beginning of the PED project, and thereafter sustained throughout the subsequent, routinely protracted planning and implementation phases. Furthermore, the motivation has to be balanced across the three main functions of PEDs, namely efficiency, generation and flexibility [2]. This consistency and streamlining would be aided by joined-up PED regulation backed by fit-for-purpose national legislation.

To classify the motivation of the key stakeholders, one can differentiate between purely financial benefits and other co-benefits [56]. There is no one-size-fits-all argument when dealing with financial motivation. Large differences exist across Europe with regard to fundamental parameters and economic incentives [57]. For example, the electricity price per unit in the Czech Republic is approximately two-thirds of the price in Germany after including applicable taxes, which extends the time period for securing returns on investment in solar photovoltaics despite subsidy programmes, complicating such an option for a range of private and public investors. It has been argued in PED practitioner discourse that the energy price volatility of 2021 along with ongoing pandemic recovery dynamics, both of which have affected all European countries, can in effect contribute to increased incentives for PED investors.

Furthermore, the energy flexibility function is closely tied to the ownership of the electricity distribution infrastructure that connects buildings in PEDs. The motivation of the distribution system operator (DSO) to engage with and contribute as a partner in local PED projects can be a critical barrier. However, the DSO's involvement can be ensured by balancing benefits, such as diversification of services, in the initial proposition put together by the PED facilitator. Intensive capacity-building of prospective facilitators may thus enhance the potential for mainstreaming and replication of PEDs.

1.3. Emerging impact: Effects of PEDs

Q8. In what ways can PEDs advance equitable economic development, i.e. socio-economic sustainability?
A8. The identification and implementation of appropriate enabling systems can ensure that PEDs become a key component and organising principle for thriving, regenerative and inclusive urban economies.

At a global level, the need for energy efficiency, flexibility and local production, as well as an increased share of renewable energy sources, is paramount. Cities have a crucial role to play here, given their outsize share of energy demand, due to hosting a large and increasing share of the global population, and their role as sites of concentrated consumption through relatively rapid urban metabolism [58,59]. Importantly, they are also sites of experimentation and accelerated innovation.

Urban stakeholders and PEDs are increasingly recognised as powerful actors and policy objects respectively, with a view to reducing economic inequality and promoting equity and economic inclusion, particularly in favour of vulnerable communities where far too many people still struggle to gain economic ground [60]. Globally, the latest available data and energy scenarios reveal that countries are not making equitable progress towards the achievement of the United Nations (UN) Sustainable Development Goal (SDG) 7: 'Ensure access to affordable, reliable, sustainable and modern energy for all'. The novel coronavirus (Covid-19) pandemic has amplified inequalities in access to resources and services, especially in rural and peri-urban areas, and has reaffirmed the need to improve energy affordability to help vulnerable people mitigate the adverse effects of the crisis [61,62].

The energy sector is fundamentally innovative, and businesses constantly present new solutions to their target consumer base. These solutions stem from understanding and responding to the needs of the people and built environment. The underlying assumption here is that by presenting a more informed assessment of the barriers and constraints faced by people in poverty in a post-pandemic future impacted by climate change, private and public stakeholders (especially the facilitators addressed in Q7) can actively involve community stakeholders from early on to formulate innovative solutions. Such partnerships – with proactive state leadership to secure public interest – are crucial to strategically co-design, select and implement bottom-up initiatives that more accurately reflect the needs and aspirations of disenfranchised people, especially in terms of the accessibility and affordability of essential energy services [63,64].

Toward the same goal, part of how countries and cities solve critical societal challenges depends on whether and how governments and decision-makers are able to respond in a timely manner to the economic crisis with appropriate and effective recovery packages and incentives, while simultaneously targeting priorities toward systemic change. Such actions would be aligned with the aim of increasing the overall quality of life of all inhabitants and boosting energy efficiency and renewable energy sources to phase out fossil fuel usage. The equitable development of PEDs is vital for unlocking the full potential of the local economy by addressing social- and skill-related barriers to inclusive decision-making while expanding opportunities and services for low-income people and vulnerable communities. Through accountable public action, community engagement, appropriate technologies, adaptive monitoring, and the support of impact finance, PEDs can reduce negative externalities, grow quality jobs, and increase entrepreneurship, stewardship, and wealth. The targeted result is thus to develop inclusive, climate-resilient and competitive neighbourhoods and cities.

Q9. In what ways can PEDs contribute to reductions in energy demand, i.e. ecological sustainability?
A9. Shifting energy production closer to consumption enables load balancing and demand response at localised scales with greater efficiencies, lower losses and scope for innovative models of energy flexibility.

PEDs contribute to reducing energy consumption, notably through increases in energy efficiency and transitioning to lower-carbon emitting sources of energy, thus measures related to PEDs have potentially positive impacts in terms of ecological sustainability [65]. Energy balancing in PEDs is the means to offset territorial consumption with generation – primarily of renewable energy – in order to attain a positive territorial energy balance. Towards this, it is necessary to ensure flexible management that involves the whole system infrastructure, from the points of energy-generation and energy-storage to energy end-use.

In order to develop and customise the energy system in a way that balances demand with generation, it is necessary to parameterise the model with whole system considerations in mind. A methodology articulated on such a principle would enable the monitoring, scaling, replication and evaluation of energy demand, and help specify in detail the characteristics of generation systems that are able to meet energy demand needs, potentially alongside the reconfiguration of some existing patterns through the use of energy flexibility solutions, including short-term and longer-term storage. PED simulations informed by real-life constraints (popularly referred to as PED labs) can facilitate refinement of holistic models of energy systems by analysing different urban configurations based on boundary conditions, capitalising on the growing knowledge base of existing PED projects under implementation [66].

Since PEDs are a key component of solutions towards a sustainable energy transition, innovative and integrated solutions are required to combine a high level of energy efficiency, renewable energy sources and smart infrastructures, in line with contextualised energy demand scenarios that leverage flexible storage, optimal energy management and ICT. PEDs should therefore go beyond a focus on energy demand reduction, as the Set Plan Action 3.2 also highlights; they should meet environmental, economic and social requirements at the district scale in sustainable ways.

District scale energy demand provides potential for energy savings, calculated on the basis of the consumption levels of included buildings within a given PED before and after intervention. The energy demand of each building is to be calculated and added to the calculations of the district energy requirements, based on monitoring calculations or, where these are not accessible, on simulation models that must be generated to have a calculation commensurable with implementation, e.g. through selective testing. Subsequent calculation of the minimum energy demand of each building to compare with the PED's energy model is to be conducted with a view to providing scenario results to relevant stakeholders such as developers, who can use this insight on building energy demand to work towards a meaningful aggregate configuration for district scale demand, including flexibility and specific spatial-temporal aspects [67,68]. There is scope to include the transport sector at the district scale by adding a layer for electric vehicle charging, but this work is still at an early stage in most contexts.

Q10. What does the implementation of PEDs imply for urban futures?
A10. Implementing PEDs can aid the successful rollout of regulatory and legislative processes that address socio-technical challenges and align economic planning and policies to leverage local strengths in a coordinated and engaged manner that empowers diverse stakeholders.

The implementation of a PEDs vision in the urban environment means the successful achievement of a powerful and attractive process of urban governance. Indeed, according to its ambitious and challenging objectives, an implemented PED project can be regarded as the result of well-harmonised joint strategies and actions that are capable of turning the existing built environment towards a high-quality, carbon-neutral ecosystem [69]. Therefore, one can consider the implementation of PEDs as synonymous with the achievement of: (a) the development and deployment of strong mechanisms to activate and aggregate energy flexibility; (b) improved cooperation between stakeholders to solve complex and fragmented implementation processes into simpler, straight-forward and replicable models and (c) an acquired capacity of communities and appetite by cities to enact low-carbon energy transitions at the district scale as a means to meet climate action commitments [1,70].

Indeed, feasible PED designs can outline bold ways to overcome several potential processual barriers. In addition to the promising technological experimentation and solutions already available on the market, ongoing efforts to achieve PED targets entail innovative solutions to enable authorisation procedures, construct sustainable business models, and craft robust collaborative stakeholder agreements. Therefore, the fulfilment of PED expectations must necessarily stem from an effort by broad, networked urban communities that feature a range of stakeholders engaged in a range of topics and dimensions of PED development [71], by (a) leveraging existing local capacity and investments, (b) prioritising action in line with their stated and prioritised objectives, and (c) monitoring and valuating well-being, health and environmental co-benefits as key attributes within targets associated with PEDs. Such innovation furthermore requires institutional support and stability through regulatory and legislative mechanisms that provide PED actors with crucial policy horizon visibility when mobilising towards targets.

Lessons learned from pioneering PED experiences should make us mindful of the high socio-economic impact of district scale investments, indirectly monetisable benefits generated, and the risk of sub-optimal outcomes [72]. Citizens, municipalities and investors all stand to be adversely impacted by a process that stutters to a halt or becomes too protracted. Both the lack of confidence in expected outcomes and the uncertainty in the development procedures of a PED can create reticence on the part of both developers and clients, with a negative impact on the PED implementation rate and on ecosystem-wide decarbonisation processes that have an urgent timeline. Promising one-stop-shop experiences and turnkey integrated service models can support PED project pipelines and financial sandboxes; such single-window clearance mechanisms are important for addressing technical and financial challenges in a holistic manner.

In sum, the development of PEDs not only implies the maturing of technological solutions and deployment, but also requires situated complementary innovations of a non-technological nature, tailored to each local urban system. Such contextualisation can help identify new feasible measures, sustainable economic models and agreements that boost available financial means and procedures (e.g. designing energy and deep renovation strategies, fiscal deduction, soft loans, access to subsidies or incentives like reduction of property tax and value added tax for stakeholders who contribute to PEDs). Each of these components is important in order to overcome decision-making barriers and to provide a reliable blueprint for an integrated design process of PEDs, which can pave the way for the implementation and replication of carbon-neutral, holistically sustainable cities.

3. Conclusions

Together, these questions and answers highlight the relevance of PEDs in relation to sustainable urban energy transitions. They provide a comprehensive picture of PEDs as constituting intertwined challenges of: a limited timeframe with urgency to implement; the necessity and importance of multi-stakeholder engagement; the complexity of design choices with customisation to context as well as transferability; the necessity to develop supportive regulatory frameworks and funding mechanisms; and the need for impact assessment, adaptive monitoring and evolving typologies to enable replicability. Key barriers include the lack of technical capacity and access to advisory services at the local level, limited citizen awareness and mobilisation alongside lack of resources for public authorities to conduct systematic outreach programmes, and a tendency to have sporadic and ad hoc interventions rather than holistic deployment of a set of complementary measures for interoperability across interventions and sectors within PEDs. Responses to the questions draw upon a variety of examples that provide evidence in support of the effectiveness of specific systems and clusters to catalyse and enable PEDs, and reflect on the role of piloting and experimentation, capacity building and facilitation, and systematic innovation platforms and governance along a deployment trajectory. Notably, the responses explicate the role of collaborative governance approaches, and measures at the urban scale that enable co-designed, locally envisioned and systematically supported PEDs in ways that are simultaneously adaptive and rapidly scalable across highly diverse urban contexts.

Some main elements highlighted across the questions and responses concern the importance of a strong position for residents in the design of stakeholder collaboration; the need to align technical optimisation with socio-economic value creation; the vital role of new regulatory protocols and hybrid business models for the design and implementation of PEDs; and the inherently integrated nature of planning required to realise PEDs in a holistic manner across multiple disciplines and domains. Clearly, the creation and sustenance of local ecosystems that represent a critical mass of stakeholders (e.g. users, owners, investors, DSOs, including both public and private entities) is vital to drive PED uptake both deep and wide. The nature of sustained social mobilisation and the legitimation of PEDs as a desirable policy object across domains (cultural, regulatory and financial) will determine the degree of success in PED implementation.

CRediT authorship contribution statement

Siddharth Sareen: Writing – review & editing, Writing – original draft, Project administration, Data curation, Conceptualization. **Vicky Albert-Seifried:** Writing – original draft, Funding acquisition. **Laura Aelenei:** Writing – original draft. **Francesco Reda:** Writing – original draft. **Ghazal Etminan:** Writing – original draft. **Maria-Beatrice Andreucci:** Writing – original draft. **Michal Kuzmic:** Writing – original draft. **Nienke Maas:** Writing – original draft. **Oscar Seco:** Writing – original draft. **Paolo Civiero:** Writing – original draft. **Savis Gohari:** Writing – original draft. **Mari Hukkalainen:** Writing – original draft. **Hans-Martin Neumann:** Writing – original draft.

Declaration of competing interest

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

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