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The Sense and Non-Sense of PEDs—Feeding Back Practical Experiences of Positive Energy District Demonstrators into the European PED Framework Definition Development Process

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Abstract: This article discusses early developments of the Positive Energy District (PED) concept, both in terms of its definition and of its implementation in real world demonstrators. Based on the specific challenges for creating an operational definition for the European +CityxChange project, the feasibility of creating a PED was practically explored by identifying 4 possible subtypes that respond to varying constraints regarding the energy balance of the PED. This article provides the context and describes these 4 ambitions levels: $\text{PED}_{\text{autonomous}}$, $\text{PED}_{\text{dynamic}}$, $\text{PED}_{\text{virtual}}$, and $_{\text{Pre}}\text{PED}$; and the 3 boundary modes: geographical, functional, and virtual. The work thus expands on the first general PED definitions as they were put forward in the SET-plan and by the European Commission, while allowing a better response to the specific boundary conditions of PEDs' physical context. As such, it provides an operational, city-focused, bottom-up PED definition. The present study analyses how these efforts connect to current work being performed on the development of a European PED Framework Definition. In the latter, new elements such as context factors are introduced in order to account for the varying boundary conditions that PEDs must address, and in particular the difficulties of realising PEDs in existing and densely built-up urban areas. Hereby it can be argued that the approach with 4 subtypes is a bottom-up method of addressing the same challenges as a context factor based approach operating in a top-down manner, this time starting from the regional or national renewable energy potentials. Both approaches indeed strive towards an optimum setup of PEDs both within their geographical boundaries and in their interactions with the surrounding energy infrastructures and cities. These efforts are instrumental in helping to prevent that a PED is being regarded as a goal in se, functionally disconnected from its surroundings. There are strong arguments in favour of handling PEDs as building blocks for the broader realisation of carbon neutral cities and regions, thus contributing to the systemic change that is needed to futureproof the built environment as a whole. Without applying this integrating perspective, PEDs risk creating a sub-optimal lock-in within their sites and thus remain one-off experiments, lacking connection to the wider urban sustainability strategies that are needed to properly address today's energy and climate emergencies. This holds even more when considering the quality-related requirements that come with sustainable urban design and governance. Therefore, this study further explores how PEDs can fully support such a deep urban sustainability transition, and what could consequently be the next steps towards successful and upscaled PED deployment.

Keywords: positive energy districts; positive energy blocks; PED concept; energy transition; climate neutrality; smart sustainable cities; Smart Cities and Communities; European energy transition; energy planning; urban planning; sustainable urban design, advanced energy systems

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1. Problem Statement

In the context of achieving climate neutrality for cities, the concept of Positive Energy Districts (PEDs) has recently gained widespread attention [1–4]. One contributing factor to this success certainly is the scale level at which a PED operates, transcending the individual building level intervention and thus opening up more and better possibilities of both advanced technical energy system integration and the upscaled contribution of many societal actors to sustainable urban (re)development. At the same time, PEDs remain an enterprise at a scale which is manageable in terms of straightforward planning and execution. PEDs thus can help to divide the enormous challenge of making cities climate-neutral into more practicable projects.

An important reason for targeting energy and climate strategies at the district level is that such an approach can deliver benefits over a building-by-building approach, both in terms of energy system design and integration and in terms of striving towards optimized urban morphology. Specific opportunities emerge regarding technical and economical scale advantages of setting up district energy systems compared to the mere juxtaposition of individual building installations, facilitating local exchanges of energy between different building programmes and mobility applications, and providing district scale energy storage systems. Integrated sector coupling, involving exchanges between electrical and thermal systems, completes the palette of such strategies. This shows that PEDs are not only advanced energy systems from the technological point of view, but also from the integration view and regarding innovative larger-scale urban deployments. At the same time, PEDs are not an entirely new concept and have predecessors such as Net Zero Energy Districts (NZEDs) [5], while district scale approaches for energy systems and the effects of urban morphology and programming on energy use have since long been studied in the research literature [5–11].

When the term 'positive energy district' was coined, there was an intention to use the word 'positive' rather than the terms (net) 'zero' (energy or emission) or climate 'neutral', thus leveraging on the positive connotation it entails. Whether such naming effectively helped the uptake of the concept would however require a specific study.

The PED concept has now been taken up beyond the original scope of the European Commission and is under study by organisations such as the European Energy Research Alliance (EERA) [12], the Urban Europe Research Alliance (UERA), the Joint Programming Initiative Urban Europe (JPI UE) [13], and the International Energy Agency (IEA) [14] for further development and roll-out. Within this, specific actors have also proposed to interpret the term 'positive' as a 'positive impact on the wider energy systems' of a city or a region, rather than just an internal positive yearly energy balance [15].

The practical realisation of the concept, in the way it was initially conceived, does however come with significant difficulties, as can be illustrated by experiences gained in recent Horizon 2020 Smart Cities and Communities Lighthouse projects (including +CityxChange). For example, it appears to be particularly challenging to realise a PED in the context of an urban district renovation project when the building density in the district is high or when many heritage buildings are present. In such a context, it becomes difficult to generate sufficient renewable energy onsite while regulatory and organisational constraints, both in the energy domain and beyond, tend to complicate matters even more. These difficulties seem, at least, to jeopardise the possibilities of implementing a narrow interpretation of the PED concept. At the same time, it can be questioned if such a narrow approach is desirable at all. Indeed, PEDs do not constitute a goal of their own but must rather be considered as building blocks of the climate neutral cities and regions of the future, whether that is expressed in the technical terms of renewable energy system integration or through the wider requirements of achieving integrated urban sustainability through high quality district design and governance.

The main research questions addressed in this article are therefore: How to improve the qualities of the PED concept and its applicability in practice? What recommendations can be drawn from experiences with past and ongoing PED pilots, in particular regarding the way these pilots translate general PED requirements into an operational working definition? How can this feed back into the ongoing research for the formulation of an EU-wide PED framework definition? These questions shall not only be addressed from a technical viewpoint, but also from the broader perspective of realising integrated urban sustainability, entailing both quantitative and qualitative considerations.

2. Materials and Methods

The research materials supporting the analysis and conclusions of the present article stem from three main sources:

1. the implementation of PED pilots in the Horizon 2020 SCC Lighthouse project +CityxChange [16,17]. These pilots are situated in Trondheim (NO) and Limerick (IE). In Trondheim, three pilot areas distributed across the city test positive energy blocks (PEBs, see further for the relation with PEDs) and local flexibility markets for exchanging and trading energy, both heat and electricity. In Limerick, one pilot area is situated in the historical Georgian city centre while a turbine in the Shannon river completes the pilot's energy infrastructure. Realising PEBs and exchanging and trading energy are also the main goals. In Limerick the pilot project includes the energy retrofit of heritage buildings. Two challenges needed to be addressed: translating the general PED definition of the H2020 call into an operational framework on the ground, and subsequently realizing the operational requirements in practice. This included substantial challenges, especially with regard to effectively building the PED pilots under the present regulatory, economic and societal circumstances. In addition, realising PEDs in existing urban districts is considered more difficult than through newbuilt areas, but the city and PED ambitions include the transformation of existing areas;
2. the editing of a PED 'solution booklet' [3] for the Smart Cities Information System (SCIS), now integrated in the Smart Cities Marketplace. The booklet was a co-production between SCIS and four H2020 SCC Lighthouse projects focusing on the realization of PED pilots: Atelier, SPARCS, MakingCity and +CityxChange. The resulting guidance document is based on a systematic analysis of the barriers and opportunities encountered in the different PED pilots;
3. participation in the Alignment Core Group for a PED definition and integrated approach (see Section 6), led by JPI Urban Europe. Participating organisations include EERA JPSC PED modules, SET Plan Action 3.2 PED Programme/DUT PED pillar, COST Action PED-EU-NET, IEA EBC Annex 83, UERA PED WG, PED-related H2020 SCC projects, H2020 SCC Task Group Replication, Scalable Cities (EU SCC Lighthouse Project group) and the Smart Cities Marketplace. The working group is thus composed of members from academia, research & technology organisations (RTOs) and the field of practice, and aims to formulate a PED framework definition that can be used throughout the EU by combining a scientifically sound approach with requirements of accessibility and ease of use by all concerned stakeholders. It operates through regular working meetings of the core expert group while broader consultations of PED stakeholders (e.g., JPI Urban Europe member state representations) provide for feedback from the field of practice.

In this way the research method for this article confronts applied case study analysis (points 1 and 2) with the ongoing transdisciplinary research for formulating a PED framework definition (points 3 and 2). The main underlying methodological framework for making analyses and recommendations in the present article is based on multimodal system analysis, a knowledge theory originally formulated by the Dutch philosopher of law Herman Dooyeweerd and subsequently elaborated in, among others, systems science and urban planning theory [9,18–21]. This knowledge theory also structures the content of the SCIS solution booklets. It has proven to be both methodologically robust and operationally performant for dealing with complex, interdisciplinary research questions.

3. Background: The Emergence of PEB and PED Concepts from 2015 Onwards

The concept of a *Positive Energy Block* (PEB) can be understood in the context of increasing European ambitions in the topics of *energy in buildings* [22] and the *energy transition* [23]. It initially emerged out of a European project demonstrator, *Hikari*, a housing complex at the Confluence district in Lyon (FR), as part of the EU FP7 EeB-generation project Next-Buildings [24], completed in 2015 [25]. It was estimated that the demonstrator displayed some performances and qualities that merited to be replicated. As Hikari had been defined as an *îlot à énergie positive* (energy positive islet), it was chosen to adapt a translation to English as '*Positive Energy Block*'. That idea was subsequently presented at an EU conference in December 2015 for uptake by the EIP SCC Marketplace (European Innovation Partnership on Smart Cities and Communities) in a new Action Cluster initiative on PEBs [2,26].

Subsequently the concept was promoted through the EIP SCC Marketplace as a way forward in scaling up zero or positive energy concepts from the building level to groups of buildings and, eventually, districts. At this stage, the PEB concept requested *"at least three connected neighbouring buildings producing on a yearly basis more primary energy than what they use."* [27] Initially, realising a functional mix (and thus also enabling useful energy exchanges between different building programmes and buildings' energy profiles) in a PEB was judged to be paramount as well, but would not yet be included in the definition. However, realising integrated sustainability would come back in later definitions. The initiators of the concept were also sensitive to a positive connotation of the wording in the definition, which is rather hard to find in terms such as 'zero emissions', 'carbon neutral' or 'zero energy' [28].

The 2018 Implementation Plan of SET-plan Action 3.2 [1] (Strategic Energy Technology Plan), developed by JPI UE [13] (Joint Programming Initiative Urban Europe) in cooperation with EERA JPSC [12] (Joint Programme on Smart Cities of the European Energy Research Alliance), EU Member States and Associated Countries and other European initiatives, set out the goal of realising 100 PEDs by 2025. In this instance, the requirement for a PED was stated as:

> "*Positive Energy Districts (PED) are energy efficient districts that have net zero carbon dioxide (CO2) emissions and work towards an annual local surplus production of renewable energy (RES). Such districts help raise the quality of life in European cities, while reaching the COP21 targets and making Europe a global role model. An open innovation framework with cities, industry, investors, research institutes and citizens' organisations all working together will help develop PEDs and the necessary R&I Activities. The approach integrates the technological, spatial, regulatory, financial, legal, environmental, social and economic perspectives.*" [29] (pp. 28–29).

Equally starting in 2018, the European Commission formally introduced PEB & PED related requirements in the Horizon 2020 project calls on Smart Cities and Communities Lighthouse projects (LC-SC3-SCC-1-2018 call) [30] (The PEB/PED requirement is included in the calls as of 2018, [31,32]). The 2018-2020 H2020 Work Programme for these calls defined a PEB/PED as an implementation goal for the innovation projects as follows:

> "*Positive Energy Blocks/Districts consist of several buildings (new, retro-fitted or a combination of both) that actively manage their energy consumption and the energy flow between them and the wider energy system. Positive Energy Blocks/Districts have an annual positive energy balance. They make optimal use of elements such as advanced materials (e.g., bio-based materials), local RES, local storage, smart energy grids, demand-response, cutting edge energy management (electricity, heating and cooling), user interaction/involvement and ICT.*
> *Positive Energy Blocks/Districts are designed to be an integral part of the district/city energy system and have a positive impact on it (also from the circular economy point of view). Their design is intrinsically scalable and they are well embedded in the spatial, economic, technical, environmental and social context of the project site.*" [31], (p. 117, [33]).

The calls featured for the first time, a requirement for PEBs/PEDs to fit into an overall Bold City Vision of city-level climate neutrality strategies. This is a step change because they do not just include more positive energy buildings, but highlight the opportunities of using a complete urban block/district and its multi-faceted characteristics. They also had an additional section on expected focus areas, which highlight further expectations and clarify ambitions and motivations:

- *"Focus on mixed use urban districts and positively contribute to the overall city goals;*
- *Develop solutions that can be replicated/gradually scaled up to city level. The technical, financial, social, and legal feasibility of the proposed solutions should be demonstrated in the actual proposal.*
- *Make local communities and local governments (particularly city planning departments) an active and integral part of the solution, increase their energy awareness and ensure their sense of ownership of the smart solutions. This should ensure sustainability of Positive Energy Blocks/Districts;*
- *Promote decarbonisation, while improving air quality.*
- *[...]"* [31]

JPI UE and EERA JPSC meanwhile set out to further develop a PED framework definition that could be used EU-wide. JPI UE held a workshop, partially based on a request for input by JPI UE for a collection of potential PED projects [34] (Positive Energy Districts and Neighbourhoods Programme—Cities Workshop and Site Visit, 3–4 April 2019, Nordbahnhalle, Vienna [35]). The event was combined with, amongst others, a +CityxChange Learning Workshop on 2 April 2019 addressing related challenges and gathering project requirements and insights [36]. A joint outcome was an initial PED definition [37] with the main characteristics as presented later in this article.

This led to the following formulation, consulted among national delegations in and beyond the EU and published in a white paper in 2020:

> *"Positive Energy Districts are 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 interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability."* [38]

This definition forms the basis for further analysis through the present article. Note that the definition leaves space for 'local or regional' energy production, thus hinting at solutions for the problem of realising self-sufficiency on the basis of on-site energy production alone. Note also the inclusion of mobility, which can be interpreted as a PED providing a share towards mobility energy use, and also optimises other mobility impacts.

Meanwhile, experiences from the field of practice such as the Horizon 2020 Smart Cities and Communities Lighthouse Projects (H2020 SCC LH) and their practical implementations were being made, testing and implementing the concept in practise. These experiences show that major challenges occur in turning existing urban districts into PEDs on the one hand from the technical and energy view and need for local generation, and on the other hand from the needed long term strategies involving multiple actors in complex stakeholder networks. One of the early outcomes was the SCIS PED solution booklet [3]. This solution booklet was co-created with participants from the H2020 SCC Lighthouse Projects +CityxChange (including authors of the present article), MakingCity, SPARCS and Atelier and thus directly translates the practical experience gained from PED pilots. It included the insight that a PED is not a product, but rather a process.

Building further on these initiatives and experiences, the COST Action PED-EU-NET [4] (European Cooperation in Science and Technology - Positive Energy Districts European Network) and the Annex 83 on Positive Energy Districts by the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC Annex 83) [14] were created to perform more in-depth collaborative research on the PED concept and its potentials, and to publish their findings.

4. An Operational PED Definition with 4 Subtypes: Addressing the Practical Implementation Challenges from a Bottom-Up Perspective

The SET implementation plan was publicly issued in 2018, and the EU H2020 work programme in 2017 for the 2018 calls, with their initial definitions as described above in Section 3. The same year, at the end of 2018, the first SCC projects granted from that call started their PEB demonstrators.

4.1. Process

These projects had a strong need for a concrete and operational working definition of PEBs that could be used in practice with cities and solution providers. An operational definition was initiated from the +CityxChange project in cooperation with EERA JPSC. The +CityxChange project [17] includes 32 partners among which 7 cities: 2 Lighthouse cities with detailed plans and immediate deployment activities in the project, and 5 Fellow Cities, which refine their plans within the project towards setting up PEBs. It was important to build an operational PEB definition that included the contexts and requirements of the different PEBs in all the cities, as a first requirement. It also became even clearer that an inclusive definition was needed. City representatives pointed out that cities each follow different development paths, which need to be possible to align with the definition. More generally, it was considered very important to not be too restrictive, as not to reduce or prevent any innovation potential towards PEBs and local development [36,39].

The process included a number of workshops such as an initial +CityxChange Learning Workshop, 2 April 2019, Vienna [36]; the SET-plan PED definition and boundaries work group meeting, 6 May 2019, Brussels (‘PED definition development v3’) [39]; and a PED workshop at the 3rd International Conference on Smart and Sustainable Planning for Cities and Regions SSPCR 2019, Bolzano, 11 December 2019 (‘PED definition development v4’). At the Brussels meeting, some reflections on the Horizon Europe Mission Area on “Climate-Neutral and Smart Cities” were included in the programme, and as such cities obviously can be considered as an upscaling from PEBs and PEDs towards PECs or PERs (Positive Energy Cities or Regions, currently not established terms) as steps towards the EU goal of Climate-Neutrality by 2050. Such strategic alignment and city-level scaling ambitions were present early for example in +CityxChange [40] and definition work [41]. Results were summarised in multiple project reports and presentations [36,39].

The workshops collaboratively developed insights in a wide range of technical and governance challenges:

- economic feasibility and cost efficiency: in particular, energetic retrofitting of existing buildings remains costly with long payback periods—often going far beyond the range of a 30 years investment horizon [42]. In the European context, most PEDs are expected to be urban retrofit PEDs. Business models that turn the PED opportunities into benefits are being developed, but many secondary benefits cannot be captured in financials while being invaluable for cities;
- optimum renewable and sustainable energy provision: in many cases, the amount of renewable or sustainable energy needed for the district could possibly be produced in a cheaper and more efficient way outside the district or the city, but such a setup would at least partly go against the PED ambition. Nevertheless this can be balanced against the reduced needs for grid upgrades or other ‘hidden’ costs;
- the stated need of PEDs to flexibly interact with their hinterland in terms of exchanging energy flows and helping to balance energy grids [38]: whereas the theoretical need for this faculty is commonly recognized, its practical implementation through operational schemes such as Energy Communities (in line with the recast EU directives in this field) is yet at the experimentation phase—see also below;
- the share of mobility energy to be provided by a PED: none of the current definitions have managed to define a desired performance level. It can be argued that mobility can only be partially included in PEDs as transport tends to act at a different scale.

Examples of emission accounting models for mobility can also be widely varying in different regions;
- regulatory barriers: beneficial local cost sharing models are not yet possible in the electrical grid and markets. Examples include no opportunity for local exchange of energy through the grid while extra wires would break the system, or feeding back energy for prosumers not being viable under present regulations and technicalities, or no feed-in tariff for surplus energy from prosumers being available, meaning they could not receive any payment [43]. Currently the implementation of the Clean Energy for All Europeans Package [44], including the facilitation of Energy Communities and peer-to-peer trading, is not yet finished in several Member States (like Belgium [45] or the Netherlands [46] to name just a few), thus prolonging the stated difficulties;
- cultural factors such as landscape and heritage value: rarely the full technical potential of onsite renewable energy generation can be realised. For example, neither shall all building roofs and façades be clad with PV panels nor shall urban wind turbines be installed wherever possible throughout the urban texture.
- organisational and governance factors: PEDs are not a status, but a process. Taking this further, PEDs are also not a single product. They are a multi-stakeholder undertaking, addressing the full complexity of urban (re)development.

4.2. Supporting Evidence from Cases

The above stated technical and governance challenges can be illustrated by examples from +CityxChange's PED pilots in Limerick and Trondheim [17]. In Limerick, the PED pilot is situated in the city's central Georgian heritage district. It is characterised by mixed use (residential and non-residential building programmes), varying urban densities in a typical range of 20 to 50 dwellings per hectare, and a strong presence of heritage buildings [3,16]. The district is in need of urban renewal. Given the urban density and the heritage character, the possibilities of both increasing energy efficiency by insulating building envelopes and producing sufficient renewable energy on-site, mainly through PV, are limited. A choice was therefore made to complement on-site renewable energy production with energy supply from a water turbine to be placed in the Shannon river, about 1–2 km upstream from the district. This implied that the turbine should be considered as a virtual asset of the PED neighbourhood, as it is not situated within the strict geographical boundaries of the PED. A number of challenges need to be addressed. First, it remains difficult to convince individual building owners to step into the PED pilot and perform substantial investments on their properties. This makes setting high retrofit standards for the housing stock more difficult. Second, current regulations do not allow for implementing the flexibility and peer-to-peer trading mechanisms needed for the operation of the PED, and special dispensation is hard to achieve, even if the EU Clean Energy Package's electricity directives have meanwhile been (partially) transposed to Member State legislation. Third, and linked, permitting procedures to allow for the placement of the turbine in the Shannon river are challenging, not the least because this regulatory case is virtually unseen in Ireland. In this way the Limerick pilot demonstrates all of the above-mentioned challenges. If all these challenges receive a proper address and the PED can be realised, another challenge immediately comes forward. While this first PED could profit from the opportunity of placing a turbine in the Shannon river—first come, first serve—more areas of the city with PED ambitions would meet increasing difficulties for realising their goals as the pool of virtual assets such as the turbine will continue to decrease. This brings forward a question of fairness and balancing: how much external energy may be reserved for a given district while not jeopardising the possibilities of other districts to become PEDs as well. This situation is a major argument to support the use of context factors and national or regional 'energy envelopes' with wider integration and balancing potential as discussed further below.

In the Trondheim case, multiple PEDs were planned in the city. As part of the deployment, work is underway to connect these and allow interaction, exchange, and trading of energy between PEDs [47]. In addition, local renewables may not be sufficient in all cases. Integration of dedicated external renewable sources is being considered, in line with the $PED_{virtual}$ concept. Challenges include as above the willingness to invest and finding suitable risk/benefit sharing models. Financing of PEDs and of overall decarbonisation efforts thus remain challenging, though PEDs can contribute with additional unlocked business models.

4.3. Outcome: PED Definition, 3 System Boundary Modes, 4 Ambition Levels

The resulting operational PED definition includes a working definition, 4 ambition levels, and 3 system boundaries [39]. The agreed working definition states:

> *"Positive Energy Districts (PED) are mixed-use energy-efficient districts that have net zero carbon dioxide (CO2) emissions and actively manage an annual local surplus production of renewable energy (RES). They require interaction and integration between buildings, the users and the regional energy, mobility and ICT system, while ensuring social, economic and environmental sustainability for current and future generations."* [39]

For the question of system boundaries, a distinction was proposed (as early as 3 April 2019 [37]) [36] and consolidated [39] between 3 modes:

- ***Geographical boundary***: *Spatial-physical limits of the PED in terms of delineated buildings, sites and (energy) infrastructures—these may be contiguous or in a configuration of detached patches;*
- ***Functional boundary***: *Limits of the PED in terms of energy grids, e.g., the electricity grid behind a substation that can be considered as an independent functional entity serving the PED; a district heating system that can be considered as a functional part of the PED even if the former's service area is substantially larger than the heating sector of the PED in question; or a gas network in the same sense;*
- ***Virtual boundary***: *Limits of the PED in terms of contractual boundaries, e.g., including an energy production infrastructure owned by the PED occupants but situated outside the normal geographical PED boundaries (for example an offshore wind turbine owned through shares by the PED occupant community).*

Based on these boundary conditions, 4 possible types of PEDs were proposed according to the realisable ambition levels. (These were initially named as Diamond, Platinum, Gold, and Silver, used in April 2019 mainly in internal documents [36], and quickly changed from May 2019 onwards into the more descriptive terms.) The ambition levels are: *Autonomous PED*, *Dynamic PED*, *Virtual PED* and *Pre-PED*, having definitions as follows [37,39,41]:

- $PED_{autonomous}$: 'plus-autarkic', net positive yearly energy balance within the geographical boundaries of the PED and internal energy balance at any moment in time (no imports from the hinterland) or even helping to balance the wider grid outside, not expected as a common case (see Figure 1);
- $PED_{dynamic}$: net positive yearly energy balance within the geographical boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages (see Figure 2);
- $PED_{virtual}$: net positive yearly energy balance within the virtual boundaries of the PED but dynamic exchanges with the hinterland to compensate for momentary surpluses and shortages (see Figure 3);
- ${}_{Pre}PED$: candidate PED, no net positive yearly energy balance within the geographical boundaries of the PED but energy difference acquired on the market by importing certified green energy (i.e., realizing a zero carbon district).

These levels were carefully chosen and developed to correspond to both a group of set points of ambition and technical potential, and to form a clear pathway of development, thus allowing for growing achievements towards high synergistical ambitions with clear milestones:

A $_{\text{Pre}}$PED does not yet achieve a positive annual energy balance by itself, but achieves it through buying green energy through outside general markets, while developing the PED. A PED$_{\text{virtual}}$ achieves a net positive annual energy balance within the virtual boundaries of the PED, allowing for adaptation of local generation sites. This situation is found in many on-the-ground cases. It reflects the challenges of direct local generation in urban areas and on any type of buildings, and allows flexibility in planning boundaries and implementation paths to include generation sites that are not building-integrated or outside the core geographical boundary. A PED$_{\text{dynamic}}$ has a net positive annual energy balance within the geographical boundaries of the PED. It exchanges energy with the wider grid, into which it is integrated. This is a type of PED that can be implemented in geographical/urban conditions that have better pre-conditions for local renewables. PED$_{\text{dynamic}}$ and PED$_{\text{virtual}}$ will be the most common types in regenerated European urban environments, allowing the built environment to act as a kind of battery for the broader energy grid. Finally, a PED$_{\text{autonomous}}$ is autonomous from the grid on the demand side—it will have a positive energy balance not on average, but at any point in time—possibly turning it into a pure energy producer from the grid view—though usually not fully a virtual power plant. Only few areas will be able to become PED$_{\text{autonomous}}$, however, in particular when other co-benefits and potential negative externalities such as urban quality of life, spatial quality, nature-based solutions are taken into account.

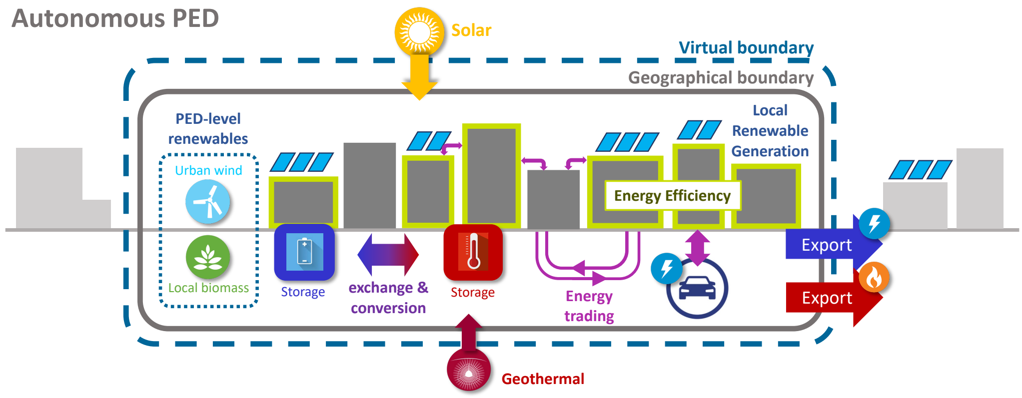

Figure 1. Autonomous PED, principle and system boundaries. Only exports to the surrounding system. Including energy efficiency measures, renewables (solar, PV, wind, biomass, geothermal, small hydropower), waste heat recovery, electric and thermal storage, integration of mobility energy needs (and EVs as batteries), sector coupling between electric and thermal.

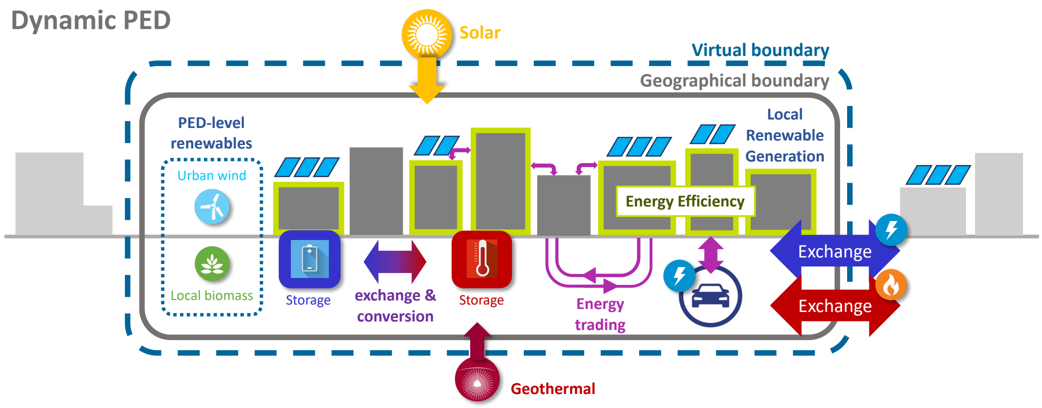

Figure 2. Dynamic PED, principle and system boundaries. Including energy efficiency measures, renewables (solar, PV, wind, biomass, geothermal, small hydropower), waste heat recovery, electric and thermal storage, integration of mobility energy needs (and EVs as batteries), sector coupling between electric and thermal, and exchange with the surrounding systems.

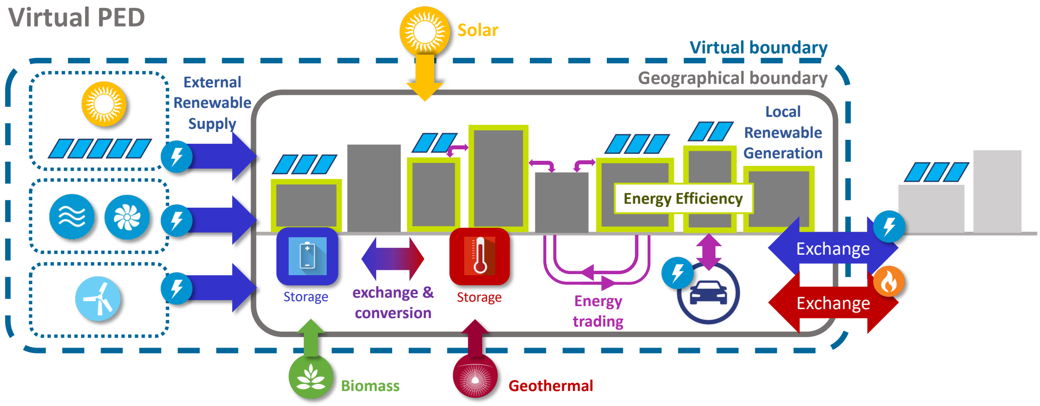

Figure 3. Virtual PED, principle and system boundaries. Including virtual integration of external renewables and exchange with the surrounding systems. Including energy efficiency measures, renewables (solar, PV, wind, biomass, geothermal, small hydropower), waste heat recovery, electric and thermal storage, integration of mobility energy needs (and EVs as batteries), sector coupling between electric and thermal, and exchange with the surrounding systems.

In summary, identifying PEDs from such differentiated perspectives would allow sufficient flexibility for adaptations to a range of different city conditions from existing projects, while keeping a certain standardisation and commonality, all within the H2020 SCC programme, the SET Plan, and future refinements. It would for example allow PEDs to import energy from outside the strict district boundaries, in situations where it is not feasible to generate all needed renewable resources onsite. This setup also interprets and translates the aspect of 'local or regional' energy production, as put forward in the JPI UE framework definition, into precise operating conditions.

The differentiation into 4 subtypes was subsequently picked up in the PED definitions of, for example, SCC Lighthouse Projects such as +CityxChange [17] (including the authors of the present article) [16,39,48] or SPARCs [49] and other projects such as syn.ikia [50].

5. From Technical Solutions to Urban Transition Governance for Systemic Change: Addressing the Contribution of PEDs towards Realising Climate Neutral Cities and Regions

The four PED types identified in the previous section are intended to also be able to tackle the second major implementation barrier for PEDs. This second barrier is strongly related to the challenge of overhauling the energy paradigm that underlies the current modus operandi of cities: decentralised fossil fuel based energy supply. In order to achieve this, deep structural change is required in all strata of society: technical infrastructures, economic setups, value chains and business models, types of collaboration between the different concerned urban actors, social rules, policies and cultural habits, up to the behavioural routines of citizens and enterprises and the (often hidden) value systems that ultimately steer all of these strata. Hereby the questions regarding energy cannot be disconnected from those regarding the adopted economic models, social justice and respect of the earth's ecological carrying capacity. In other words, effectively solving this puzzle simultaneously requires realising overall integrated sustainable functioning at the level of the district or the city [20].

The four types of PEDs are created to be able to support the following main transition challenges.

From the simple, individual short term solution to complex, collective long term formats: it becomes increasingly obvious that many preferable set-ups for PEDs and, at the higher scale level, climate neutral cities, require different configurations and business models than current standard practice. The four types of PEDs, in particular the $\text{PED}_{\text{virtual}}$ and $\text{PED}_{\text{dynamic}}$, will be able to support a shift in preferred assets from individual ones such as the individual heat pump, the individual PV installation on the individually energyretrofitted home or the individual electric car, towards collective and integrated assets such as micro district heating and cooling networks, shared renewable energy generation installations managed by local energy communities, sustainable collective- or co-housing, and shared or collective mobility solutions including mobility-as-a-service (MaaS).

Aligning interests and agendas of the different urban stakeholders: in order to achieve these solutions, the interests, agendas and investment horizons of a multitude of urban actors in complex stakeholder networks must become sufficiently aligned in order to arrive at a shared development process. This requires new organisational set-ups and business models, new collaboration formats with new types of legitimacy and an overall strong co-creation and governance process that facilitates all of the former. The integrated set-up of the $PED_{dynamic}$ and $PED_{virtual}$, with intensive interaction between building, grid, mobility, ICT and citizen experts and end users, will favour cooperative financial and partnership models to optimise economic sustainability. It is to be noted that also established PED definitions such as the ones formulated by the SET-Plan, the European Commission and JPI UE refer to quantitative (energy and carbon related) aspects as much as qualitative (sustainable development related) aspects. This implies that those definitions recognise the fact that both challenges, stated in the context of the present analysis, need to receive a full address. Studying the full spectrum of deep systemic change in cities is however beyond the scope of the present article. It is nevertheless necessary and sufficient to indicate that PED challenges must be linked to the wider issues at stake for sustainable urban development, of which reaching climate neutrality is one important pillar. Taking into account the two main challenges as stated above will hereby provide for a good starting point. It assures that PED strategies and agendas can be fully integrated in urban (climate) action planning.

6. Current Work on an EU-Wide PED Framework Definition: From PED Types to Context Factors—Situating PEDs in Their Wider Energy Generation Landscape

Through the PED definition work undertaken under the umbrella of JPI UE, an alternative approach has emerged to accommodate for the different contexts in which PEDs operate. These developments have been documented and shared for consultation through a working paper [51]. This reviewed draft version processes feedback from dedicated stakeholder workshops on 17 and 20 September 2021 (EERA Joint Programme Smart Cities, Nordic Edge conference) as well as main comments from an IEA workshop on 22 October 2021 (IEA Annex 83 on Positive Energy Districts).

Instead of addressing these boundary conditions by distinguishing 4 subtypes with increasing degrees of self-sufficiency, the approach is reversed. Whereas the subtypes start from a bottom-up vision, analysing how much 'exterior help' a PED needs given its starting condition, a top-down manner of addressing the same constraint consists of situating the PED in its wider energy landscape and deriving a proportional contribution of the PED to the total renewable and sustainable energy generation capacity of the considered region or country. In this way, a fair '*effort sharing*' mechanism can be established between the PED and the other areas of the region, whether they be urban or rural. Hereby, '*context factors*' define the specific characteristics of the PED, allowing to propose a justified amount of effort sharing that can be assigned to the PED. The basis of this mechanism is derived from work on system boundaries in the energy system [52,53].

More precisely, these context factors will account for:

- **Urban density**: the higher the urban density, the more difficult it becomes to generate all needed energy on-site. Therefore a reversely proportional context factor can be applied, allowing the district to self-generate lower shares of its operating energy with increasing urban densities;
- **Heritage**: the more heritage buildings or protected views are present in a district, the more restrictions there will appear on building envelope interventions and the installation of renewable energy generation capacity such as PV panels. Therefore,

another reversely proportional context factor will allow to reduce the self-generation share of the district with increasing heritage value.

- **Mobility**: it should be pointed out how much of the mobility energy for the users of the PED shall be generated onsite. This is a discussion that remains far from established, even for PEDs that can be considered as having the potential of generating 100% of their own energy needs. As mobility strongly relates to higher functional scale levels than the district itself, it may be expected that the mobility energy produced in a PED will always remain a share of the total mobility energy needed by its users, be they inhabitants, commuters or visitors;
- **Climate** and embedding in the regional or national energy system: each region has its own challenges to address in terms of generating sufficient renewable and sustainable energy. In this way, the regional energy equation may be more difficult to solve in a context of cold and dark winters with high heating demand and little available resources to supply heat pumps, versus warm and sunny summers with dominant cooling demand and ample potential for PV-input. The complete energy balance for the region will thus influence the share of energy production that is assigned to a PED.

Such an approach implies that national or regional effort sharing mechanisms must be established and quantified, which lifts the needed level of solution building to a higher scale. From an overall viewpoint of reaching climate-neutral functioning in the most ecologically efficient and cost effective manner, this is indeed a logical step to take. Heat and cold balances will to a large degree be addressed by a regional approach, while for electricity an EU and beyond approach remains preferable. It is to be noted that sector coupling may further change the working parameters. For example, the future import of green hydrogen may become an important factor in the overall energy equation.

Whereas current PED definitions hint at integrated sustainable urban development, the above method with context factors goes even further by situating cities in their regional or national energy hinterland – and beyond. This leads to an approach of full-scale subsidiarity, whereby the integration of macro-, meso- and micro-scale energy generation is being realised at the methodological optimum [9].

7. Conclusions and Outlook

The present article discusses PED development from a practical implementation viewpoint, reflecting on the evolving definition framework and suggesting approaches that may help to make PED development more feasible while at the same time integrating PEDs meaningfully in their surrounding (energy) systems and living environments. This is considered both at the technical level of a positive yearly energy balance and zero greenhouse gas emissions, and at the level of PEDs supporting integrated urban sustainable development, thus becoming an effective building block towards creating climate neutral and smart cities. Specific indicators related to PEDs, including energy, carbon, LCA, economic and qualitative indicators, are not in scope for this article and will be addressed in future developments of the wider European framework definition.

The use of an operational PED definition with 4 subtypes helps to address a PED's practical implementation challenges from a bottom-up perspective. The 3 system boundary modes and 4 ambition levels provide a practical framework for projects, cities, and developers to work with. The 4 PED subtypes, and the Dynamic PED and the Virtual PED in particular, also allow to effectively address qualitative requirements for PEDs as well as to enhance their embedding in the surrounding environment both from the technical and the integrated sustainable development point of view. We discuss this with selected case studies and examples to show how it can help support project implementation. Further case studies will be part of future work.

Meanwhile a top-down approach for PEDs is also under development, whereby the same implementation challenges are being tackled by considering the total renewable energy potential of a region or country as the starting point for setting the PED's specific energy requirements. Thereby context factors account for the different starting positions for PED development, for example when a PED project regards urban retrofit, includes high-density urban fabric, or contains many heritage buildings.

Both approaches serve the same goal: providing an operational and practical approach towards building PEDs, while allowing for flexibility in the PED definition requirements.

In terms of the formulated research questions, we conclude that the case-based bottom-up approach and the research-based top-down approach do meet each other regarding practical solutions for the technical energy balancing of PEDs. However, three differences can be noted. First, the top-down method accounts of the sustainable energy potential of the wider region or state, thus assuring 'fair share' access to this overall potential by different PEDs. Such an approach prevents a 'first come first serve' strategy that could be the consequence of using the bottom-up definition in a case-by-case fashion, without considering its impacts on the wider energy system. Such risk occurs foremost in the case of virtual PEDs, and with limited outside potential for renewable generation. Second, although an approach based on context factors would therefore be preferable, the latter method requires that the total energy potential of a region or country is first established and that proper allocation keys are identified before any individual PED can be built. However, this would only become relevant if PEDs would become a significant fraction of the energy transition. The current state rather shows that we are too slow, and any fast deployment is preferable from our view. Third, the bottom-up approach allows qualitative requirements for PEDs to be addressed in a flexible and context-sensitive way that allows for fast deployment. Addressing qualitative aspects of PEDs in the top-down work organised by JPI Urban Europe is still in its early phases.

Next recommended development steps therefore include:

- Further mapping on-the-ground experiences in creating and managing PEDs, to extract viable technical, social and economic pathways to PEDs for use by cities, real estate developers and other urban decision makers. In particular, further elaborating context factors to account of the wider sustainable energy potentials and inquiring practical feasibility of this method;
- In this way, developing a definition framework that is at the same time sufficiently precise to allow PED benchmarking, sufficiently flexible to accommodate for the many contexts in which PEDs will be developed, and sufficiently simple not to repel urban actors such as city administrators, project developers or building owners in using the definition framework;
- Further investigating the quality-related factors, co-benefits and potential negative externalities of PED applications better, and identifying how these may contribute to generating willingness to invest in PEDs (public, private and citizen funding);
- Analysing which efforts are best fit at district or at city level, to see PEDs as important stepping stones towards climate-neutral cities and regions. This makes PEDs not only targets in themselves, but establishes them as growth and transition enablers.

Overall, this continued work on framework definitions and real-life demonstrators will contribute to successful and upscaled PED deployment within the urban sustainability transition.

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