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Energy Production, Efficiency and Flexibility for Positive Energy Districts: A Review

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Abstract. In 2018, EU launched the programme “Positive energy districts and neighbourhoods for sustainable urban development” with an aim to support the planning, deployment and replication of 100 Positive energy districts (PEDs) by 2025. This is an ambitious target considering the various challenges on implementing PEDs. This paper, based on literature review, provides an overview on the challenges and possibilities on the three main components of PEDs; energy production, energy efficiency and energy flexibility.

Keywords: Climate Goals, Energy Transition, Cities

1. Introduction

Cities have large potentials for supporting sustainability and combating challenges such as climate change, environmental degradation and health issues. Moreover, literature suggests that districts and neighbourhoods within cities hold significant possibilities for change [1] to reduce energy and greenhouse gas emissions. In a study by Nematchoua [2], the potential for urban, rural, and sustainable neighborhoods to mitigate GHG emissions and energy consumption were investigated. They estimated that the GHG emitted by neighborhoods could be reduced with 53-97% by 2050. Moreover, rural neighborhoods with substantial building renovations/energy efficiency measures and PV production potential in the area can reach carbon neutrality by 2050 [2]. Recently the focus has expanded from individual houses to seeking possibilities of city districts and neighborhoods [1], which can lead to new innovative solutions and synergies. Districts have several advantages for energy solutions compared to individual buildings, such as energy exchange between buildings, community storage, better renewable energy (RE) production potential, and other possibilities to reduce the energy input and use [3]. EU launched the programme “Positive energy districts and neighbourhoods for sustainable urban development” with an aim to support the planning, deployment and replication of 100 Positive energy districts (PEDs) by 2025. Positive energy districts are defined in the white paper 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” [4], which can be considered as an “initial definition” for PED [5]. An important characteristic of the PED definition is the holistic view and understanding of the systems and integration between sectors [4]. “Positive Energy” refers to energy surplus wherein local or virtual energy production from renewable energy exceeds consumption within a time frame and as per Derkenbaeva, et al [5], “district” refers an entity larger than a block or a neighbourhood. The energy exchange involved is considered in primary energy [4]. Nevertheless, there is still no common universally accepted definition for PEDs [5].

The lack of a standard and consolidated definition for the PED concept is considered as one of the main limitations for PED development and deployment in European cities [6]. Various projects and research are dedicated to further explore the definition to facilitate widespread implementation of PEDs. For example, IEA EBC-Annex 83-Positive energy districts (2020-2024) is developing a more unified definition for PED, and evaluating technologies and planning tools which can aid PED implementation. https://annex83.iea-ebc.org.

In addition to the energy issues, the PED definition includes other objectives such as social concerns, inclusiveness, solutions to energy poverty, district wide considerations on the transportation networks and design optimization [7]. Nevertheless, the focus of this paper is on the challenges and possibilities of the three main components of PEDs; energy production, energy efficiency and energy flexibility.

2. The three "pillars" of PEDs

Energy production, energy efficiency and energy flexibility form the basis for the general PED framework. Renewable energy options are one of the main contributors to the transition towards climate neutrality, and is evidently of high priority in any project with the aim of a sustainable future. Energy efficiency is the second requirement for PED projects, and should ensure that the renewable energy used in the district is efficiently used and not unnecessary exploited and wasted. Energy flexibility, the third component, reflects that urban areas are among the largest energy consumers in the world [4], and is considered an important aspect [8]. Thus, all three aspects are important for a successful PED project in urban areas [4].

2.1 Renewable energy production

Renewable energy production within the district is encouraged on PEDs, and if energy needs to be imported then RE sources are prioritized. Three frameworks based on the energy flows are suggested for PED definition [9]: (i) Autonomous PEDs which is self-sufficient for energy with no need to import energy and characterized by clear geographical boundary; (ii) Dynamic PEDs, which is also characterized by clear geographical boundaries, nevertheless, they are more open and are allowed to export and import energy and only requires a yearly energy surplus.; (iii) Virtual PEDs, which has a virtual boundary, can for example include an energy production facility that is outside the decided geographical boundary, but owned by the PED occupants. A fourth category of PED that has been suggested is candidate PEDs, which is not positive energy balance annually, nevertheless can become one by buying certified green energy from outside general market [10]. In many cases the renewable energy required for a district to become PEDs could possibly be produced in a cheaper and more efficient way outside the geographical district or city [10], thereby favouring virtual PEDs. However, Hedman et al. [7] identified three concerns with virtual boundaries: who owns the energy provided, who is responsible for business models, and how the origin of energy is secured. Vandevyvere et al [10], also highlights the fairness aspects on virtual RE solutions, with an example from a case study in Limerick in Ireland, wherein a decision to use a water turbine in Shannon river 1-2 km upstream from the district (virtual solution for that district), could jeopardize other districts possibilities to become PED in using such resources.

As per Bruck et al [11], the districts in southern Europe (closer to equator) are favourable for the economic viability of PED projects. On the other hand, districts which are already connected with district heating (DH) may have a significantly higher cost [11] to become PED. This is partly attributed to lower operating cost and also lower GHG emission from DH system as compared to the individual fossil fuel boilers. Further, Bruck et al [11], estimates that in zone 5 in Europe (Stockholm) only 26% of energy demand can be covered by local resources and hence the zone is much more grid dependent than in southern zones. According to a sensitivity analysis by them, in zone 5 the net present value is drastically reduced due to requirement of large battery installation (upto 3.8 MWh). The district energy storage lead to less electricity being imported, which in turn reduces associated GHG emissions. However, the study by

Bruck et al [11] is basd on several simplifications such as building stock, occupant density, their behaviour, energy performance of the building was the same across the studied regions. Similarly, the study included only a few energy sources such as photovoltaic, battery, air-to-water heat pumps and electric boiler.

As per Zhang et al. [6], the most common RE implementations in PED projects are solar energy, district heating/cooling, wind and geothermal energy, of which PVs are the main source in almost all projects. As per a FP7 project investigation on energy positive neighbourhoods, the surplus electric energy produced by positive energy buildings mostly comes from photovoltaic system rather than wind turbine or other sources. However, urban density limits the possibilities to generate RE locally through PVs [10]. Nevertheless, a calculation based on 3D urban data model in a German district of Ludwigsburg suggest that PV systems on all available roofs could cover up to 77% (technical potential) of the electricity consumption [12]. Weather conditions is one of the major factors that influence energy consumption of the building stock [13]. The seasonal variation of available solar energy is larger in northern Europe, and there is a mismatch due to the larger energy demand during winters. PED projects in Mediterranean countries have high potential for PVs while possibilities for solar energy are more limited in northern Europe as compared to southern Europe. Yurui et al [14] found that, by scaling up the current PV production, the production of local solar energy could cover the electricity demand of the investigated building in southern Sweden during summer months. However, for an annual self-sufficiency, the energy consumption during winter months is hard to cover due to limited space. As per a study that interviewed a few Swedish professionals, who have experience in PED projects, the “positive energy” and “annual surplus” terminologies in the PED definition may be unsuitable for Swedish conditions and a few interviewees were of the opinion to have a shorter timeframe [15]. However, further studies are needed for identifying optimal timeframes [15].

The necessary legal and strategic frameworks for the realization of PEDs are not in place in many cities [16]. In Sweden, till recently, it was not allowed to share energy between buildings. This was reported as a major challenge for implementation of PEDs in Sweden [15]. However, from the beginning of 2022 the legislation was modified in Sweden and it is allowed to create local energy networks and share energy between buildings and facilities [17]. The local regulations regarding DH might obstruct the implementation of PEDs. For example, all buildings in Denmark are required to be connected to the green DH and thus investment cost increases when aiming for positive energy balance. Prosumer concept which has relevance within PED context is also faced with variation in regulations among member countries [7]. For example, in Spain the self-consumption regulation makes the balance on a monthly basis, while in Latvia it is on a yearly basis. In both countries the users will not be reimbursed if the energy export exceeds their electricity consumption [7].

2.2 Energy Efficiency

Energy efficiency is another requirement for PED projects, and should ensure that the renewable energy used in the district is efficiently used and not unnecessary exploited and wasted. Nevertheless, the reference framework based on national consultations (Reference Framework for Positive Energy Districts and Neighbourhoods) suggests to give energy efficiency priority as the space needed for RE generation is limited, especially in urban areas [5]. Energy efficient retrofitting is critical to achieve PED in districts with colder climates and denser population [18]. As per [19], it is difficult to reach positive energy buildings in urban areas in Nordic climate if all buildings’ energy demand is included. They suggest that in such situations the investment cost in the energy system would be 47-62% of the life cycle cost, and the rest is operational cost. Based on the study in three climate zones in Europe, Bruck et al [18] suggest that energy efficient retrofitting results in improved grid resilience due to lower peak exchange. In hot climates, energy consumption due to increased need for cooling and the increased use of air conditioning is expected to increase drastically, especially under the negative influence of global warming. The effective use of passive cooling can reduce the cooling energy use under heatwaves and reduce the likelihood of power outages [20].

According to an analysis of the projects in the PED booklet by Bossi et al. [21], about two third (66%) of the PED projects listed in the booklet focus on mixed areas (both existing buildings and urban areas with newly built projects). Vandevyvere et al [10] also highlighted that it is more difficult to realize PEDs in existing urban districts as compared to the newly built areas. The existing residential areas can be problematic to refurbish, and also hold other issues, such as social and organizational aspects [4], and buildings' physical limitations. The challenges get exacerbated in historical districts with regulatory limitations for retrofitting [22]. The energy efficient retrofitting of existing buildings is costly with a long payback period and often difficult to justify from energy cost reduction [23]. However, other benefits associated with energy retrofitting is difficult to show in financial terms [10]. Bossi et al [21] acknowledges the challenges of the existing building block and its importance in Europe, and proceeds to propose further efforts within the area, such as focusing primarily on new/mixed housing and then replicate suitable solutions to the existing building block.

Bruck et al. [18] identify a lack of studies regarding passive retrofitting in PEDs, such as improvements of the building envelope and windows, and focuses on concepts with similar features as PEDs, such as nearly zero energy buildings/districts (NZEB/NZED) and zero energy buildings/districts (ZEB/ZED) in the background to their study. They summarize studies that evaluate passive and active renovation strategies in buildings and conclude that in most cases, passive retrofitting is required to achieve low energy-demand and high-standard buildings and districts, even though it is not as economically viable as compared to active retrofitting, such as PV installations and heat pumps. However, passive measures are considered important to lower the carbon impact of buildings.

In their study, [18] evaluates the importance of building envelope retrofitting for various European climate zones and conclude that the further north the district is located, and the denser it is populated, the more valuable retrofitting is to create a PED. In most cases, refurbishment is the determining factor whether it is feasible to turn an existing district into a PED, except for some cases in southern Europe. In their study, they found that renovation in northern areas will have a larger economic value compared to warmer climates. From an environmental point of view, the authors found that refurbishment measures will lead to reduced GHG emissions in the district, regardless of climate, and that a higher standard of retrofitting leads to lower grid-related emissions. Retrofitting the district also displays some flexibility potential, such as a more grid-supportive behavior, and significantly lower peaks in central and northern Europe, as compared to southern Europe.

According to [8], energy modelling and simulation, performance assessment, information technology, and business model development are a few of the challenges for the development of PEDs. Urban building energy modeling (UBEM) tools facilitate the modeling of a building stock and help design and optimize energy systems on an urban scale [24]. Additionally, bottom-up, physicals-based tool such as City Building Energy Saver (CityBES), City Energy Analyst (CEA) and Urban Renewable Building and Neighborhood optimization (URBANopt) can support decision-making for increased building energy efficiency through simulations and the detailed analysis of what-is scenarios using simulation results. However, as per a review [25], existing energy modelling software has challenges for use in PED study, due to issues such as input data and its customization, grid impact, the complexity of multi-energy interaction and information on district infrastructure. Despite the increasing number of UBEM tools, problems such as the lack of standardization, lack of useful, structured and complete data for UBEM development and lack of performance indicators that link UBEM results with PEDs hamper the effective use of urban-scale models during PED development.

Hence developers of new urban energy tools created their own tailor-made data models, while municipalities use their own database structure to collect and manage urban information [26]. It is reported that most of the existing studies are based on self-developed PED assessment approach [11]. For example, Moreno et al. [27] in MAKING CITY project proposed an 8 step PED calculation methodology. Research Centre on Zero Emission Neighbourhoods (ZEN) in Smart Cities, Norway developed KPIs within seven categories: GHG emissions, energy, power/load, mobility, economy, spatial qualities and innovation [28]. However, [28] cautions that these KPIs are not tested and will be modified subsequently and moreover, the list does not have KPIs for spatial qualities and innovation as they need to be developed.

2.3 Energy Flexibility

Annex 67 defines the energy flexibility of a building as "the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements" [29]. A review on demand side flexibility in Northern Europe suggest a technical potential of demand side flexibility in the range of 15-29% of its peak [30]. A study in buildings in Milan suggest that the concept of sufficiency, efficiency and flexibility need to be considered together to have a realistic chance to achieve PED [31]. Their study suggests that to achieve annual net zero energy balance by only improving the supply (installing heat pump and DHW and PVs on roof top) would require land for PV installation of approximately 3.2 times that of the footprint of the buildings. If energy efficiency (for example, envelope renovation) along with sufficiency measures (for example, reducing energy use of conditioned space and distance travelled by household in electric car by approximately 60%; from 127.3 $KWh_{electric}/m^2$/year to 53.5 $KWh_{electric}/m^2$/year and from 11885 km to 5000 km, respectively) are included along with the above supply side improvement then it is possible to achieve annual zero energy balance without extra land space if "reasonable" amount PVs are incorporated into facades [31]. However, energy balance in winter would require additional space of 1.5 times the footprint of the buildings [31].

Realization of positive energy districts is expected to significantly increase the share of renewable energy in the electricity system. As per a study by [32], the flexibility requirement of power systems would increase dramatically when the combined share of wind and solar power generation become greater than 30% of the annual electricity consumption. The requirement for flexibility would be less for geographically large, transnational power systems. Rinaldi et al. [33] underlines the significance of juxtaposing the energy flexibility provided by HVAC systems such as heat pumps and domestic hot water boilers with the electricity energy generation through PV panels, and thereby significantly increasing the local PV self-consumption. Junker et al. [34] evaluated the significance of energy flexibility in tackling the integration of immediate, fluctuating renewable energy generation to an electricity grid, which necessitates demand side control strategies to mitigate the transition of the two systems. This evaluation concerns PEDs as they are multi-layered systems that aim to integrate renewable energy production and existing electricity grid. The study by [34] is relevant to the topic as they introduce a 'flexibility function' which interlinks a specific smart building or a cluster of smart buildings to a penalty signal.

An important transition to consider when planning and designing PEDs is within the transport sector [9]. Fossil fuel-driven cars are being replaced with electricity-driven vehicles, and thus the demand for renewable electricity will increase in the coming years to cover the demand of the transport sector [9]. The surplus energy in a PED could cover parts of the demand, supporting electric mobility in the district and in other areas [35]. The district approach mentioned within Article 19 of the revised Energy Performance of Buildings Directive (2018/844), highlights the link among urban planning, buildings and mobility [31]. However, one of the outcomes from the various workshops and working group meetings to discuss and define PEDs was that mobility can be included only partially in PEDs as transport sector tend to operate in a different scale [10].

Energy storage can be important for realizing the ‘flexibility’ requirement in a PED and Lindholm et al. [9] reviewed energy storage methods (such as pumped hydro, compressed air storage, batteries and thermal energy storage) and their suitability for various applications/situations. One example regarding virtual PEDs is that they could utilize both renewable energy sources and storages outside the geographical boundaries to a greater extent compared to dynamic and autonomous PEDs [9]. Erba and Pagliano [31] highlighted the utilization of thermal energy storage in the building envelope to achieve positive energy targets. Two advantages of such a measure are that the peak periods are reduced, and possibilities to store RE when there is an excess of energy in the grid.

Within the demand side energy flexibility, smart scheduling of electrical household appliances could play an important role in shifting the electricity demand. Li et al. [36] drawn attention to data-driven models in achieving energy flexibility through the developments of smart sensing, artificial intelligence, and machine learning technology. However, they also underline major drawbacks of data-driven methods such as necessitating high-resolution data for the deployment of the model, and critical domain expertise regarding the field, which can potentially hinder digital modeling studies in PED studies.

3. Conclusions

This article provides a brief overview on the challenges and possibilities on energy production, energy efficiency and energy flexibility within the context of PEDs. The absence of a consolidated definition for PED is considered as a restricting factor for the take-off of PED concepts. However, a universal outline of PED suitable for all cities and climates is hindered by various factors, such as national and local regulations, resources, energy systems, economic, climate-related differences and planning culture. The three “pillars”, especially energy production and energy efficiency, are used in urban planning and construction and professionals have experiences to how they can be used to improve areas towards more sustainable districts. Considering and optimizing the three “pillars” of PEDs is a next step towards a holistic view on local energy systems in neighborhoods, however, it has several challenges and thereby needs further multi-disciplinary research in this field.

Data availability statement

This is a literature review study based on published articles/reports and does not involve any specific data.

Underlying and related material

No material other that than stated in the paper was used during this study.

Author contributions

Conceptualization and writing original draft: Gireesh Nair:
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Competing interests

The authors declare no competing financial interests or personal relationships that could influence the work reported in this article.

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