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An Exploratory Study on Swedish Stakeholders' Experiences with Positive Energy Districts

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Abstract: Positive energy district (PED) is a novel idea aimed to have an annual surplus of renewable energy and net zero greenhouse gas emissions within an area. However, it is still an ambiguous concept, which might be due to the complexity of city district projects with interconnected infrastructures and numerous stakeholders involved. This study discusses various aspects of PED implementation and presents practitioners' experiences with the PED concept, challenges, and facilitators they have faced with real projects. The study is based on interviews with ten Swedish professionals. The major challenges reported for PED implementation were local energy production and energy flexibility, sub-optimization, legislation, suitable system boundaries, and involvement of stakeholders. Most of the interviewees mentioned improved collaboration, integrated innovative technology, political support, and climate change mitigation goals as important facilitators. The interviewees highlighted the importance of a local perspective and considered each city's preconditions when developing a PED project. The study emphasizes that to facilitate PED implementation and replication in cities, more knowledge and clarity is required about PED such as on the definition and system boundaries.

Keywords: positive energy district; energy transition; sustainable urban development; stakeholder perspective; replication

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1. Introduction

Even though they only cover a small geographical share, cities are the main contributors to the current depletion of resources, climate changes, and rapid global warming [1]. The population in urban areas will grow if the current urbanization rate continues, and it is expected that 70% of the population will live in cities by 2050 [1]. There will be a significant increase in resource consumption and energy demand in cities if the current consumption pattern is not changed [2]. Besides the effects cities have on climate change, they are also key for the transition towards a sustainable future [1].

McCormick et al. [1] summarize three advantages of district-sized projects: (i) compared to single buildings, the size allows for more innovative solutions and possibilities, (ii) districts provide a larger perspective than buildings, infrastructure, transport, and public space, yet easier to "maintain" than the entire city, (iii) district-sized projects have a better chance of engaging local stakeholders, business, academicians, and residents. Since districts have a "closeness" to the residents, climate change measures and energy issues can be brought into peoples' everyday life which might increase acceptance and knowledge of innovative solutions such as facilitating installments of photovoltaics (PV) in the area or creating energy communities [3]. Future changes within energy systems, such as an increase in PV energy generation, use of electrical vehicles (EV), better integration of technologies, better coordination between buildings and grid [2], and mismatch between energy demand and on-site renewable energy (RE) generation [4], can be more effective if addressed at the district level, rather than at building level.

A positive energy district (PED) is an innovative concept proposed for reaching climate targets [5]. The strategic energy technology (SET) Plan Action 3.2 Smart Cities and Communities established the PED concept in 2018 [6], with the main goal to accelerate the energy transition and aid sustainability [5]. JPI Urban Europe compiled lessons from national consultations in a white paper "Reference framework for Positive Energy Districts and Neighborhoods" (henceforth referred to as the white paper) [5]. According to the white paper [5], the idea of a PED is to have a defined city district which produces more energy than it consumes on an annual basis, thus creating an energy surplus which can be stored or exported to other areas. Energy efficiency, energy flexibility, and local energy production of renewable energy forms the foundation for PED. Innovative and smart solutions will be used to limit energy use in the area while optimizing production and utilizing flexible solutions. Four guiding principles are mentioned: quality of life, inclusiveness, sustainability, and resilience, which broadens the concept and enables a more holistic approach with a focus on the residents as well [5].

A standard and consolidated definition for PED is not yet explicitly set, but the minimum requirement is a "group of connected buildings" [5] while it has also been suggested that the district should be larger than a building block or neighborhood [7]. However, it is mentioned in the PED white paper that the size might need a national definition [5]. To create a common plan for PEDs, the joint programming initiative (JPI) Urban Europe has developed a program that supports the development, positioning, and replication of 100 PEDs in Europe by 2025 [6].

PEDs are still in an early stage and a few aspects of PEDs, such as its definition, how to define system boundaries, and energy and emission calculations are ambiguous for many stakeholders. It might be partly due to the complexity of holistic city projects with integrated energy systems. Due to the complexity and novelty of the concept, identification and clarification of processes behind PEDs, such as motivators, cross-sector collaboration, driving forces, facilitators, and challenges, are required to facilitate implementation [8]. Further, the identification of challenges and opportunities might facilitate the evaluation and replication of PEDs [9].

The involvement and cooperation of stakeholders on a national level is a priority for PEDs [5] to address the complexity of urban districts and development [10]. The PED framework should correspond to the priorities of urban practitioners in the field as well as global energy and urban policies to create good implementation processes which account for national and geographical differences and preconditions [5]. It is suggested as a future step to continuously gather experiences from real projects to aid PED development, " . . . PEDs are not a status, but a process" [10]. Hearn [11] provides stakeholders' perceptions on PEDs with a specific focus on energy vulnerability. Studies that present the perspectives of stakeholders, with experiences from PED-related projects, can provide insights on various aspects of PED features that might be relevant for ongoing and future projects. As per the authors' knowledge, there are no studies that discusses the perspectives of practitioners on definition, challenges, and facilitators to PED implementation. A better understanding on the experiences of PEDs and similar city projects might contribute to enhance the knowledge on the topic and thereby facilitate more cities to strive for a positive energy district.

This article contributes to the existing knowledge on PED by focusing on the perspectives of professionals with PED experience. The interviewees are associated with existing and planned city projects in Sweden that have characteristics and similarities to PEDs such as PED-like and PED-related projects. The professionals' reflections on the PED definition, main challenges and facilitators and issues on replication are highlighted. This study summarizes Swedish experiences on early "PED" projects that may provide pointers for the widespread adoption of PEDs in Sweden and elsewhere. This study also highlights a few research gaps in PEDs that need consideration and further investigation.

In this paper, we first present background on PEDs as well as important characteristics and studies on the concept that are relevant for the research aim (Section 2). In Section 3, we provide the methods. Section 4 presents the results and discusses the outcomes and conclusions are presented in Section 5.

2. Positive Energy Districts

As described in the white paper [5], a PED is a city district that produces more energy than it uses on a yearly basis, creating a net positive energy surplus from RE. Existing literature uses different terminologies to describe a project that has similar characteristics as a PED but does not fully achieve PED requirements such as PED-related [7,12], PED-like [13], candidate-PED [14], pre-PED [10,14], and towards-PED (To-PED) [6]. PED projects have mostly been implemented in newly built urban areas [6]. As new constructions constitute only a small percentage of the built area in Europe, new urban areas will have an insufficient impact on the reduction of greenhouse gas (GHG) emissions [15,16]. Thus, implementation and replication of PEDs in existing areas will be important [15] and is listed as a main challenge for achieving climate neutral cities [5].

There are discussions on whether to have timeframes other than yearly to define PEDs, such as seasonal [17], monthly, or life cycle for energy balance calculations. One advantage of a shorter timeframe than yearly would be to improve the balance between energy demand and local energy production, thus considering the peak energy demand [7]. Erba and Pagliano [17] studied how a yearly and seasonal (winter/summer) timeframe affected the energy balance in a district and the required land area for PVs to reach a positive energy value. They found that it would be more difficult and also require more land area to achieve a positive balance for the seasonal timeframe as compared to the yearly timeframe. Their results indicated an overproduction during summer and partly covered demand during winter. The authors mention that some countries are using partial compensation on net energy use, for example, within a certain period in a month. Similar methods might be used to account for the shortcomings of a yearly balance on the district level [17]. As per Fichera et al. [18] the optimal dimension of RE production and energy storage in the district needs to be investigated since too much installed production and storage potential might lead to buildings being mostly self-sufficient which limits the sharing potential. This could restrict flexibility opportunities in the district, which might affect the success of the PED.

Integrated innovative technology is mentioned as a key perspective to PEDs and is necessary in achieving annual energy surplus [15]. It is also mentioned as a key challenge [8]. To ensure that energy systems are reliable, there is a need for better flexibility options such as storage [19] or demand side management [5]. Furthermore, there will be an increased use of intermittent RE and electricity demand due to higher use of EVs in the future [19]. There might also be social issues associated with technology, such as end-users lack of engagement and resistance to change, for instance opposition towards PV installments in the area.

In a workshop [14] which was organized as a contribution to the SET Plan Action 3.2, three boundary conditions were proposed: geographical, functional, and virtual. Another outcome from the workshop was the identification of four different classifications of PED: autonomous, dynamic, virtual, and candidate-PED (pre-PED). The four classifications are based on energy flows and boundaries of the project and have been applied in existing PED projects [10]. Candidate-PED has no yearly positive net energy balance, but imports certified green energy, and is thus a zero-carbon district. Virtual PEDs have virtual boundaries (i.e., not geographical), while autonomous and dynamic PEDs both have clear geographical boundaries. Autonomous PEDs are completely self-sufficient at any given time, but they are connected to the external grid to enable the export of surplus energy. Dynamic PEDs are allowed to export and import energy with the requirement of an annual energy surplus. Autonomous, dynamic, and virtual PEDs are further elaborated in [19].

Preconditions are important to include in PED planning processes and they vary among the European countries [19]. A few examples of preconditions are cities' climate and energy policies [5], population, energy consumption behaviour, development and achievements within the building sector, access to resources and renewable energy sources (RES), and waste heat [19].

2.1. The PED Framework

The PED framework is based on three pillars: energy efficiency (EE), energy flexibility, and energy production [5]. Local RE production is an important contributor to the transition toward climate neutrality [1]. If or when energy needs to be imported, RES is prioritized [5]. Since a PED is a district that produces a surplus of RE on a yearly basis, the excess energy can either be stored locally or be exported outside the district boundary and thus supporting the transition towards a greener city [2]. However, energy should not be unnecessarily exploited and wasted, and thus it is important to employ EE measures in an early stage to reduce the energy demand [5,20]. Energy flexibility will contribute to creating a largely independent system and higher flexibility also increases the resilience and strength of the systems on a regional level [5].

A universal PED profile suitable for all cities and climates is hindered by variations in each city's preconditions [5]. Thus, instead of a general process for all PED cases, a broad framework was suggested to enable national adaptations. The focus is on both energy functions and sustainability goals [21], to consider different preconditions and allow projects to adapt to local and national conditions [5]. The minimum PED requirements are expected to gradually increase to harmonize the differences in the national requirements [5]. The broad PED framework ensures that To-PEDs or similar projects have the potential to be transformed into a positive district [22].

Regulatory frameworks are reported to be a challenge for PED implementation [21]. A few suggestions to avoid those issues are improved efforts on Key Performance Indicators (KPI), minimum requirements for PEDs, and developing standards and certifications for realized solutions in PEDs [21]. It is important to investigate whether certifications at the building or district level could serve as the foundation for a future PED certification or label. Emphasis should be on a holistic view to avoid issues that might appear when focusing solely on individual buildings or solutions [21].

2.2. System Boundaries

System boundaries and calculations of emissions, energy use, and energy balances for PEDs are not specified in the white paper [5]. Similar to the framework, the system boundaries are open for local and regional interpretation due to different preconditions in European cities [5]. Currently, only the residents' energy use within the district is included in energy calculations. However, there are discussions on whether other aspects, such as water and waste management, transportation, mobility [2], and grey energy [5], should be included in the district's system boundary.

Energy flows over system boundaries and inside the district are very specific to each case and might be complex [8]. Since there are currently no standards for energy balance calculations, an approach could be to use building standards, and scale them up for districts [4]. One example of how to apply existing standards for buildings is in [23] three different balance concepts for net-zero energy buildings (NZEB) are proposed: import/export, load (energy use)/generation, and monthly net balance. In another study by Shandiz et al. [4], the authors use those three balance concepts for NZEBs and apply them on a district perspective. The balance concepts (import/export, load/generation, and monthly net balance) are discussed in terms of zero emission communities and energy master plans. The authors found that load/generation balance is more suitable for a district perspective compared to the other two, since it focuses on emissions and energy targets instead of interaction with the larger grid. A load/generation balance would also account for non-RES as well as RES, compared to import/export balance, and it is better suited to be applied with existing building codes. Erba and Pagliano [17] discuss some drawbacks with an import/export energy balance. Issues with flexibility in the district and energy storage might appear such as increased energy use in the area due to energy losses related to the storage which needs to be accounted for in energy balances and may also lead to flexibility being overlooked.

3. Methodology

The study is based on a semi-structured interview with ten professionals in Sweden. The selection of the interviewees was based on their expertise with PED-related projects. All interviewees were involved or had been involved with PED-related projects and had an interest in the topic. The majority of the interviewees were selected from a PED workshop conducted in December 2020. The workshop was organized by Viable Cities [24], which is a strategic innovation program in Sweden that focuses on the transition towards sustainable cities. All the interviewees, who were chosen from the workshop, had relevant experiences on PED-related projects. The remaining interviewees were chosen based on “snowball sampling” wherein the interviewee provided the name of potential interviewees who have experience in PED-related projects.

The majority of the interviewees were engineers but also included a biologist, two environmental scientists, and one communication expert. Hereafter, the interviewees have a designated abbreviation based on their organizational affiliation such as M1 for a person from the municipality and U1 for the utility (Table 1). Five of the interviewees are from four municipalities, while three interviewees are from utility companies. Of the remaining two interviewees, one works in a science park, and the other person is from a citizen-led innovation platform. These two persons were categorized as ‘Others’, and henceforth are referred to as O1 and O2 (Table 1). Three of the ten interviewees were women.

Table 1. Interviewees’ abbreviation based on their organizational affiliation.

Organization	Abbreviation
Municipality	M1, M2, M3, M4, M5
Utility	U1, U2, U3
Science Park	O1
Citizen-led innovation platform	O2

The ten interviewees represent seven projects in Sweden: Brunnshög, FED (fossil-free energy district), Hammarby Sjöstad, Nanna, Norra Djurgårdsstaden, RUGGEDISED, and Tamarinden. Three projects are facilitated by the municipality, RUGGEDISED, and is a smart city project funded by European Union’s Horizon 2020 research and innovation program, and Johanneberg Science Park was the coordinator of one project. The remaining two projects are led by the Royal institute of technology (KTH), Stockholm and ElectriCITY. The projects are located in five Swedish cities, and of the seven projects, three were initiated after 2019. Three projects have a district size between 2–2.4 km^2, and one project is 0.05 km^2. The latter project will have around 7000 apartments, while the other three projects (mainly residential and commercial areas) will make housing for between 20,000 and 40,000 residents, and two of the projects reported that there will be 20,000 and 35,000 workplaces in the area, respectively. Of the remaining three projects, one is based in a parking garage and two are located at campuses.

Two interviewees who were with different organizations worked on the same project (U3 and O1), and one interviewee did not work with a specific project but was involved in several projects similar to PEDs (U2). Two interviewees were from the same municipality (M4, M5) and worked on the same project and were interviewed together.

The interviews were conducted online on Zoom in April–June 2021. Each interview lasted approximately one hour. The interviews were based on a semi-structured approach and as per Silverman [25], “one of the strengths of qualitative research is its ability to assess directly what happens in the world”. This suited the aim of collecting real-life experiences from PED-like projects. The questions asked include “What PED-related project(s) are they involved?”, “What were the reasons for starting the project?”, “What is the aim of the project?”, “Which actors are involved?”, and “How is the project organized and financed?”.

Besides questions regarding the interviewees' specific projects, they were asked about general thoughts and opinions on PEDs such as "What are the biggest challenges/facilitators for a successful PED?" and "What are the biggest challenges/facilitators for replication of PED projects?". A few examples of possible challenges and facilitators were provided to the interviewees who asked for clarification. The response might have been different if the interviewees were asked to rank on major challenges and facilitators.

A few of the interviewees could not answer all the questions due to time constraints. Further, a preliminary review of the interview results showed ambiguity in a few responses that called for clarity. Accordingly, a follow-up interview of about 30–60 min was held with seven persons. All the interviews were recorded and transcribed. The quotations presented in this paper were translated by the authors.

Since none of the projects completely fulfilled the existing PED definition, hereafter the interviewees' projects are referred to as PED-related projects. The increased focus and interest in PEDs have led to several new projects in Europe with PED ambition. The study might have missed a few projects that might have been initiated in the last couple of years in Sweden and thereby does not include perspectives of practitioners from those projects.

The interviewees were selected based on relevance, which is purposive sampling, where samples are chosen based on relevant features. Nevertheless, it is likely that some individuals who have experience in PED related projects are missed in this study. Further, the qualitative approach in this study with relatively few samples may limit the generalisation of the results.

4. Results and Discussion

All interviewees mentioned that the project they are involved with did not start with an ambition to have a yearly positive net energy balance. The projects rather evolved later as a PED-related project. All seven projects have characteristics and ambitions that are similar to the PED definition. However, five of them do not achieve a positive energy balance over the system boundaries, while two projects are considered partly a PED by the interviewees. One interviewee (M3) considers his project an important component in future PEDs. Two main reasons for the interviewees not to consider their project as a PED is the ambiguity related to the system boundaries (M2, M4, and M5), and the energy demand in Sweden might be too high to achieve positive energy districts (M1, U1, O2). Another possible reason why the projects in this study do not completely reach a PED status may be because most of the projects were planned and initiated before the PED definition was introduced in 2018.

Two out of the seven projects are listed in the JPI Urban Europe's booklet [6] as To-PEDs by the participating stakeholders. One of the two has the ambition to become a PED. The other project is in a city that has a goal of producing more energy than it consumes, and thus the overall city goal matches the PED definition.

Table 2 summarizes a few of the project-related information as reported by the interviewees. Three projects were implemented in existing building blocks of which two are on university campuses, two in newly built areas, and two projects are in areas that have both old and new buildings. Three of the PED-related projects are currently in the "active" phase, one project is under construction stage and was described as "in all phases", i.e., various parts of the districts are either in the planning, implementation, or active phase. The others are involved with projects that are either in the planning or in the design stage. Thus, the projects are implemented in various urban contexts and phases, and thereby provide information from different situations. However, it might act as a limitation and further studies could focus on one specific phase and either old, mixed, or new areas, to get a more in-depth perspective.

Table 2. Project information as reported by the interviewees.

Project Name	Interviewee	Facilitated by	Project Stage	PED Pillars	External Funding	City Planning Involved	Citizens Involved	Buildings
Tamarinden	M1	Municipality	Design phase	All three	Not yet	Yes	No	New (residential)
RUGGEDISED	U1	A large EU funded project	Active phase	Efficiency and flexibility	Yes	Yes	Yes	Existing (campus)
Brunnshög	M2	KTH	Idea/planning phase	All three	Not yet	Yes	No	New (residential, commercial, industry)
Hammarby Sjöstad	O2	ElectriCITY	Active phase	All three	No	No	Yes	Mixed (residential, commercial, industry)
Norra Djurgårdsstaden	M4, M5	Municipality	All phases	All three	Yes	Yes	To some extent	Mixed (residential, commercial)
Nanna *	M3	Municipality	Pilot phase	Flexibility and production	Yes	Yes	Yes	Existing (parking garage)
FED (Fossil-free energy district)	U3, O1	JSP and the city	Active phase	All three	Yes	No	Not initially	Existing (campus)

* Part of a larger project.

All projects except one had political support and a top-down organizational structure. Most interviewees mentioned that a top-down leadership structure is better for sustainable city projects. Only one of the projects in this study has a bottom-up citizen initiative, and two interviewees (U2, O2) consider such leadership advantageous. Bottom-up leaderships, such as grassroots initiatives, are democratic and decentralized [26]. It may increase approval and support for transitions and changes needed in cities, such as lifestyle changes and technical implementations, for example by encouraging local RE production [1,26]. As described in [7], several PED projects in Europe are both initiated and led locally by citizens, where social identity, trust, and power relations in the area have been listed as central aspects. Despite if the projects were initiated top-down or bottom-up, social factors were key for stakeholders to initiate and implement them [7]. As more local energy projects in districts are developing with a high commitment from citizens, the processes of bottom-up structure need more studies. Especially since the interviewed actors considered top-down more beneficial for PEDs, further research could investigate these two approaches for PEDs.

Several interviewees mentioned that the profitability of a project is important, and two interviewees (M1 and O2) mentioned that the payback period of their PED-related project is attractive. M1 stated that the payback was relatively short, and the profitability might be positive for stakeholders due to current models and price lists. O2 mentioned that all models that have been proposed for implementing technical solutions in the district have so far been profitable.

All seven projects have investigated and included innovative solutions. For example, one project utilized energy from a fourth-generation DH system and another used waste heat from high-risk waste incineration. One project developed an intelligent knowledge network for trading energy, and a project in its design phase plans to utilize waste heat to share electricity and heat between buildings with a low-temperature DH system.

The outcomes of the interviewees' responses are structured under four categories: general reflections on PEDs, major challenges, major facilitators/benefits, and replication (Figure 1). The topics they discussed most under each of those categories are also provided in Figure 1.

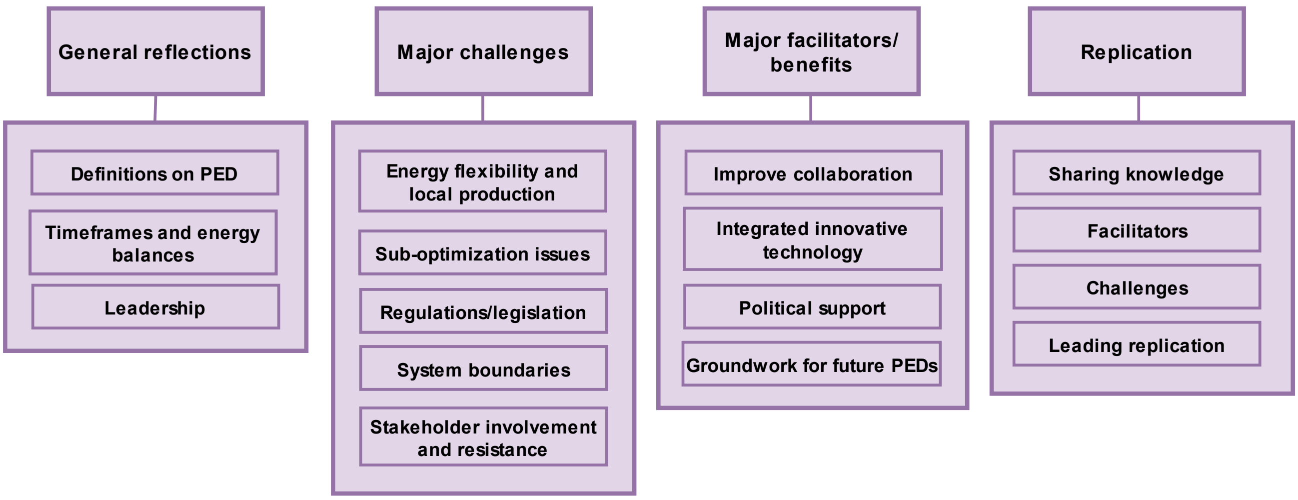

Figure 1. Structure of the interviewees' responses on general PED projects.

4.1. General Reflections on PED

Several interviewees stated that a wide-spread implementation of PEDs would contribute to climate change mitigation. One interviewee from the municipality (M4) mentioned that PEDs might be used in their city district as a tool to reach their climate goals. One project was initiated by politicians who felt the need for a sustainable development for the growing city. The urban/city planning group at the municipality is involved with all except two projects. In one project, city planning was not involved since nothing was built, the project was implemented in an area with old buildings. Instead, focus was on having efficient solutions for energy, as well as flexibility and local production of RE. In the other case, the organization that initiated the project has a dialogue with the city planning office to explore possible collaborations.

Two interviewees (M1 and U2) both had similar arguments regarding district-scale projects, such as PEDs, and the positive impact they might have on the city. Especially if new innovations and technologies are tested in the district, and thereafter components and parts of the solutions can be replicated and used in both existing and newly built areas. One of the two (M1) considers that a holistic view is vital when working with district-scale projects. Additionally, most of the interviewees mentioned the benefits of a test bed. One interviewee (U2) thought that districts are perfect to use as test beds and that all cities should use and learn from them. He also thought that test beds should explore various measures for PED while only a few measures would be possible to replicate, and thus it is important to choose the right measures for replication projects.

4.1.1. Definitions on PED

One interviewee (U2) discussed the origin of the concept of PED and concluded that it has been invented in a context where heating and electricity are produced using fossil fuels. Further, according to U2, Sweden is unique compared to most other European countries, with nearly zero fossil-fuel-based energy production. He also mentioned that a different approach might be needed as sustainability targets are different in Sweden, compared to other countries in Europe, with large biomass resources and a nearly green energy system. This relates to the PED definition and studies on PED [19] and self-supplying communities [27], which highlight the importance of regional adaptations and consider local and national preconditions and challenges for the implementation of PEDs.

The interviewees have different opinions regarding the definition of PED. For example, several interviewees consider the existing definition as a limiting concept and with the wrong focus. One interviewee mentioned that if the effort is focused on solely creating a positive district, then it may result in overlooking other important issues. For example, an area with highly efficient buildings may have low operating energy. However, the construction of those buildings may result in significant carbon emissions. Several interviewees disliked the words “independence” and “self-sufficiency” in the PED definition, as it could create an illusion of a self-sufficient district when it is not and it still needs support from outside the boundaries.

4.1.2. Timeframes and Energy Balances

Four interviewees were sceptical of the wordings such as “yearly basis” and “annual surplus” in the concept, due to large seasonal variations of climate in Sweden. According to one interviewee (U2), it is very difficult, if not impossible, to achieve an effective annual energy surplus in cold climates.

“We have to be cautious with this definition yearly basis, because energy [such as solar] will be in abundance during summer and also cheap during summer months. The 2–3 coldest and darkest weeks during winter will be critical, that will define the entire context”.

The interviewees argued that the surplus energy in summer will be irrelevant during the coldest winter periods in Sweden as in high latitude regions, there is a mismatch between the availability of RE and energy demand during summer and winter. This indicates that the focus on yearly positive energy could be deceptive and misleading from the real situation since potential may be there in summer but cannot be used to create an annual energy balance. Further, if energy is imported during winters there might be associated CO_2 emissions depending on energy sources, and thus the district may struggle to reach net zero emissions targets [17], even though on a yearly basis there is a positive energy balance due to summer production. Accordingly, “useful” energy surplus might be more relevant as compared to the “net” energy surplus.

The energy demand would better match production if the timeframe was shorter than a year such as monthly or seasonal [7]. The energy systems on the production side could be dimensioned to better fit the actual demand; however, it often leads to oversizing of the systems [28] since the energy demand is higher in periods and the energy grids need to be sized accordingly [17]. It would be more challenging to reach energy positivity for a seasonal or monthly balance compared to yearly due to the seasonal discrepancies between RE production and demand [28].

As per the authors' knowledge, currently no specifications exist on how to evaluate and calculate energy consumption or CO_2 emissions in a PED. It is mentioned in the white paper [5] that a review of calculation approaches for CO_2 emissions will be made to investigate how to account for the fluctuating nature of RES, of which one solution is an hour-by-hour method. However, it is mentioned that annual averages cannot be used in the hourly method, since it would not be clear if the locally produced electricity in a PED replaces renewable or fossil-based electricity. Zhang et al. [12] discuss that one reason why most PED-related projects are choosing a yearly scale instead of a shorter timeframe might be due to the lack of energy storage in major energy strategies. Large seasonal storages will have related land use, materials and costs, and unavoidable energy losses [17] that need to be part of the planning and design of districts. Erba and Pagiano [17] investigated yearly and seasonal energy methods, and they also discuss shortcomings with storage used with an import/export energy balance such as increased energy use in the district due to energy losses and thereby conflicts with flexibility goals.

Properly evaluated RES that are suitable for the local situation [19], energy storages [12], and a suitable timeframe [17] should be investigated to account for the climate and seasonal variation of RES. Further studies are needed to investigate how the concept of "annual surplus" or other timeframes for energy balances such as seasonal or monthly could be applied in cold climate.

4.1.3. Leadership

The leadership structure can be either top-down or bottom-up, where the top-down approach is led by provincial authorities or NGOs [26]. Most interviewees consider municipalities can take the initiative and the leadership role in PED projects. This is similar to a suggestion by [21] that cities could take the leadership role in PED projects as it is relatively easier for cities to involve relevant stakeholders in projects. The reasons being mentioned are that the municipalities have existing associations with stakeholders and clear climate and sustainability goals encompassing social and economic sustainability aspects. Further, two interviewees believed that the lead should have a dedicated focus on the progress of the city, aiming for holistic solutions (M3, U3). According to several interviewees, academia can contribute to PED discourse, however, not in a leadership position. Two interviewees (U1, O2) thought that a citizens' initiative could successfully take a leadership role, while the majority considered a top-down initiative as a more suitable leadership approach. The fragmented opinion on the most suitable lead is most likely due to the various subcomponents and complexity involved in PED projects. A suitable lead for specific PED projects, either top-down or bottom-up, needs further evaluation.

As per O1, no organization wants to take the leadership role. One reason mentioned was that such projects might not be considered serious by relevant actors. Some companies were uncertain whether the product they will test in a PED project would be profitable in the market since the focus area may change after the project time. Moreover, some actors were not fully interested because there were no economic driving forces.

4.2. Major Challenges for PED

All the interviewees mentioned local energy production and energy flexibility as a challenge for PED implementation. Seven interviewees consider sub-optimization and legal barriers as challenges for PEDs. The next most reported challenge (five) was on deciding the system boundary. Three interviewees consider resistance from stakeholders, problems with financing, and changing consumer behavior as major challenges. Fewer (two persons) consider the inclusion of mobility, citizen commitment, and integration of regional energy systems as major challenges. One interviewee stated that the increased number of EVs will create issues such as increased demand for charging points and electricity. The electric cars will cause high peak demands which need to be dealt with, and it is important to investigate solutions since a network expansion will be expensive. Figure 2 presents the interviewees' responses to the major challenges of PED implementation. The challenges that were mentioned by two or more interviewees are presented in the figure. One interviewee (U3) involved with a PED-related project in the active phase argued that since there are few PED projects in operation, more challenges may be identified later on when more projects are implemented.

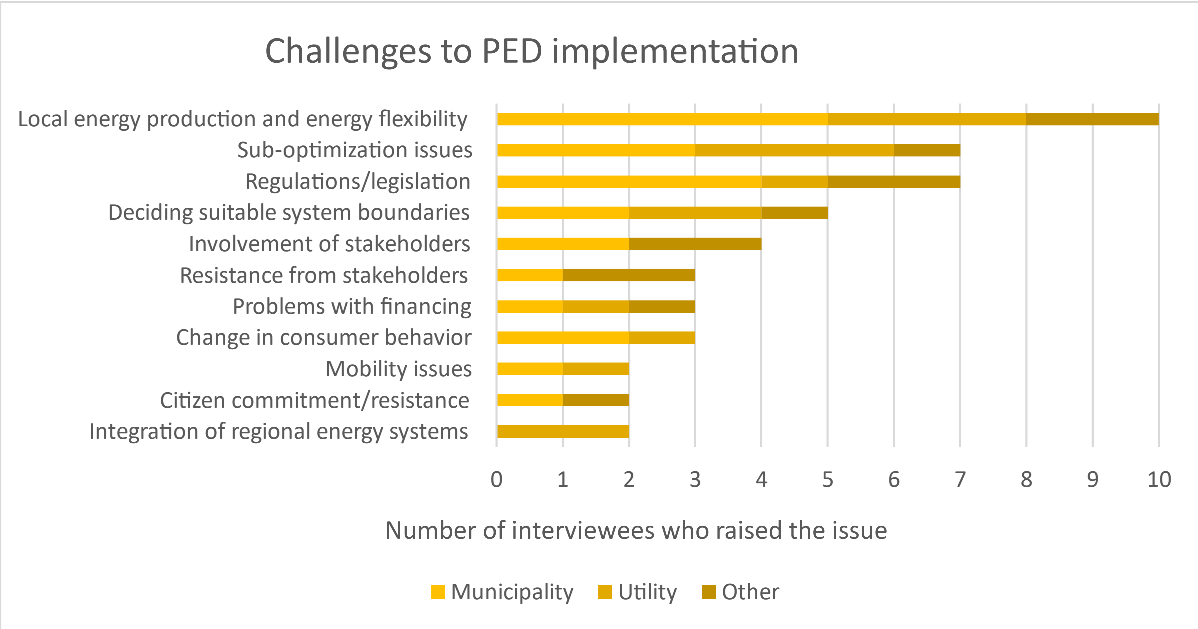

Figure 2. Interviewees' opinions on major challenges towards PED implementation, ordered based on their affiliation.

4.2.1. Local Energy Production and Energy Flexibility

All interviewees discussed energy flexibility and local energy production and challenges that could arise when implementing PEDs in Sweden, and how various aspects could affect the energy parameters. Discussions related to this specific theme are provided under subsequent subsections. The majority of the interviewees mentioned the benefits of including DH in smart city districts. Four interviewees (M1, U1, U2, and O1) stated that in Sweden and other countries with similar climates the most critical times of the year to avoid capacity shortage are the coldest weeks. Seven interviewees reflect that DH should be used for heating since it is mainly using waste heat or energy from waste incineration, and one (M2) mentioned that it will lead to sub-optimization if the large DH system is not included in PED. Even though there are CO_2 emissions related to waste incineration, the waste energy should arguably be used as otherwise it may be an unexploited resource.

One example that was mentioned separately by three interviewees (M1, U2, and O1) is that if heat pumps are used for heating, then it may lead to the use of non-RES during peak heating periods (cold winter) as the heat pumps require electricity, and RES might not be available during those periods. They argued that it might lead to sub-optimization and could be an issue in Sweden since heat pumps are a common alternative to DH. Even though heat pumps require less energy and mainly use fossil-free sources, they could contribute to an increased electricity demand when outdoor temperatures are very low, which may increase the need for fossil fuel-based back-up power in the grid.

An issue with locally produced RE is that people may not prefer to have energy production facilities near where they live. One interviewee (M5) described how people might perceive local energy production:

"Not in my backyard, feel free to produce electricity on the Scanian plains or in the northern forests, but not in Stockholm".

She (M5) mentioned that the majority of people lack awareness of how the energy they use is produced, and it might be a barrier to production and/or increasing the share of local RE. She thought that it is important to use RES on a regional level, to increase awareness among citizens and increase understanding of what is required to produce energy.

Other challenges mentioned in local energy production (M1 and O2) were delivering RE across the country, as well as the availability of space in cities for RE production. One interviewee (O2) mentioned that there was not enough space for PVs in their project area and thus they investigated other solutions. A potential solution was to build a PV park outside the system boundary, which would be a virtual solution. However, such solutions are currently economically unviable. He mentioned it might be profitable in the future with political decisions and new tax regulations.

4.2.2. Sub-Optimization Issues

Most of the interviewees reported concerns with sub-optimization in PED projects. A common issue that was mentioned was the loss of a holistic view and a larger system perspective leading to negative consequences for the city. One interviewee (U2) thought that it was important to have a pragmatic view and not solely focus on theoretical solutions. Another interviewee (U3) mentioned that sub-optimization issues may be solved by deciding on proper system boundaries and having a system perspective. This indicates that further studies on sub-optimization are required to identify issues and find solutions for existing and future PEDs.

Several interviewees also mentioned issues with isolated islands, and one interviewee (M1) considered it as a major sub-optimization issue. According to an interviewee from the utility (U3) it would become problematic if there were isolated islands in the city that think they are energy independent when in reality they are not. For example, in cold climates, the district would rather have energy surplus during summer and be energy deficient during winter, and thus needs to import energy during winter. Avoiding isolated islands can, according to another interviewee (U2), be conducted by identifying which factors should be handled at the district level, and which should have a larger system perspective. An example mentioned by U2 was to exclude heating from the definition of PED and instead keep heating on a city level, while electricity should be managed on a district level.

A few studies consider the heat and electricity flow in a district separately. The thermal and electrical profiles in the districts will differ and need separate balances. In [29], the authors present how self-sufficient the district is in terms of heat and electricity, and in [30], the thermal and electrical balances in a district are shown for various scenarios. If the results are presented separately and clearly such as in percentage [29] or with heat and electricity cover ratio and self-consumption ratios [31], it might be easier to recognize which measures to implement to reach overall energy positivity and to optimize the selection of technologies [30]. On the other side, it might be beneficial to create synergy effects between sectors, especially in urban areas due to the density of energy infrastructures [5].

Two interviewees (U1 and O1) did not consider isolated islands an issue in Sweden. The interviewee from the utility (U1) reasons that a possible path towards large-scale implementation of PED is by starting with isolated islands that are continuously integrated into the city and with other PEDs. This is because otherwise, the task at hand would be too broad. Another interviewee (M3) mentioned that it could be better to start focusing on components for a PED (such as an efficient parking hub) which will then add up to a PED project with a holistic structure. On isolated islands, an interviewee (O1) does not think off-grid solutions are suitable in cities, PEDs should instead support and strengthen the larger systems while mostly managing their own operation:

" . . . in certain situations, the owner of the larger network will think it is great that the small local energy system will manage itself and lower their peaks, and in other situations it will be the opposite, we have no electricity now, lucky that we can get some from the larger network".

Sweden has a well-structured DH system, which uses mainly RES. Hence, the isolated islands may be less concerned in Sweden as compared to many other European countries. One reason for the disagreement in the discussion on isolated islands could be the few numbers of PEDs and To-PEDs in Sweden, and thus limited experience from active projects. By using different definitions and classifications for various scenarios and projects (such as dynamic, autonomous, and virtual PEDs [19], and suitable balance concepts [4], issues with isolated islands might be avoided since the energy import and export will be thoroughly designed according to the districts and the project's conditions.

4.2.3. Regulations/Legislations

Most interviewees mentioned regulations/legislation as a main challenge, which is also a commonly reported barrier in studies on PED-related concepts [9,32]. Seven projects in the PED booklet reported challenges with legislation [6], and it is mentioned in the white paper [5] that the necessary legal frameworks are not yet in place in many cities. Vandevyvere et al. [10] mention regulatory barriers as a challenge discussed in PED workshops, such as no feed-in tariff, and no opportunity for local exchange of energy. Hedman et al. [2] discuss different national regulations from a PED perspective and how they might be obstructing PED projects. One example was regulations for district heating in Denmark wherein all buildings in Denmark needs to be connected to the green DH network. Due to this requirement, the district may have to import heat, and thus there needs to be more measures to counter the bought energy, such as local RE production and EE measures. If heat can be produced in the district rather than imported, it would have been easier to reach the annual surplus. This could be challenging especially when PEDs are defined by physical system boundaries. Another example in [2] is prosumer regulations. Spain and Latvia limit the payment of exported energy, which might discourage potential prosumers to install RE production and reduce the potential for local production. Uspenskaia et al. [9] report a lack of standards, open data formats, and protocols as a few legal barriers to the replication of PEDs. Further, city projects are occasionally sub-optimal due to legal bottlenecks, such as spatial planning being seen as constant, when in reality it is constantly transforming, and EU directives being interpreted differently after being translated into national legislation [33].

One interviewee (M1) stated that regulations obstructed one of their project's main objectives, which was to share energy between buildings via a local energy network. Another interviewee (O1) had experience from a completed project where they created an exchange network for energy, a local energy system with a trading market. According to her this innovative approach resulted in increased EE in addition to improved energy flexibility in the area.

"When we could transfer and utilize the energy better, share [energy] with each other, the results lead to energy efficiency improvement at district level".

One of the most discussed legal barriers during the interviews was the Swedish legislation on sharing energy locally between buildings. However, some regulations are being evaluated and modified. For example, shortly after the initial interviews, two test beds in Sweden (which are both among the interviewed projects) were given the opportunity to try solutions without being restricted by the Swedish electricity law on sharing energy locally. At the end of March 2021, the two projects were allowed to investigate possibilities to share electricity between buildings, creating a local energy market in the community with support and financial aid from the Swedish Energy Agency. One project is a newly built district and the other is an existing district, which could provide good learning possibilities for future PEDs. In October 2021, the Swedish electricity law was changed, and from the beginning of 2022, it is allowed to create a local energy network and share energy between buildings and facilities [34]. Thus, one of the legislations most interviewees mentioned as a challenge to the implementation of PEDs has changed in Sweden. Accordingly, this may not be a major challenge in Sweden anymore, and the legislative change might facilitate innovative ideas and the mainstreaming of PEDs in Sweden. Nevertheless, this barrier could be relevant in many other countries.

4.2.4. Deciding Suitable System Boundaries

Deciding suitable system boundaries was a theme that inspired the most discussion among the interviewees, and the majority thought it was a major challenge for PED implementation. A few interviewees suggested including other aspects in the system boundary such as mobility, water treatment plants, and hospitals, which have significant CO_2 emissions. Two interviewees (U2, O1) thought that only energy use of residential buildings in the district should be included in the system boundary, and not for example airports, since they are part of the larger system and emissions and energy related to such activities should not be assigned to the small district. However, one interviewee (U2) argued that emissions, such as waste- and energy-related, that are produced outside the boundaries but related to activities within the district should be included within the system boundary. Similarly, according to another interviewee (U1), airports, hospitals, and other high energy-demanding facilities should be included if they are within the geographical system boundary. They have included the hospital area in their PED-related project.

One interviewee from a municipality (M2) mentioned that the system boundaries are crucial when discussing the concept PED, since a poorly chosen and designed system boundary might lead to wrong focus and sub-optimization. Even small differences in system boundaries can decide whether a district is energy positive or negative. His project had a very sensitive system boundary, and one question they discussed in the project was whether to include high energy-demanding facilities in the district within the system boundary. These facilities are part of the energy system in the area, waste heat from the facilities provides heat to the district via a low-temperate district heat system.

"It depends on how we calculate the energy consumption within the research facilities [high energy-demanding units]. If we include them, they consume huge amounts of energy. If we do not include them, then we become energy positive".

In that specific project, if the research facilities were included in the district, the project would not be able to achieve a positive energy balance over the year as the energy demand would be larger than the local RE production. Moving the system boundary by a few meters, thereby excluding the research facilities, would change the energy balance significantly. The interviewee (M2) argued that if a few meters on the system boundary decides the energy performance of the district, then it is better to have less strict boundaries and concentrate on energy issues and reducing GHG emissions. He argued that it would be irrational to have a "boundary line" determine the success of a project. Another interviewee (M1) dislikes the idea of a system boundary since even though it could be highly efficient within the boundaries, sub-optimization issues might appear if emissions outside the boundaries are neglected.

Wyckmans et al. [14] propose three boundaries for PEDs: geographical, functional, and virtual. The geographical boundary corresponds to the spatial-physical limits of the district, the functional describes the limitations of the energy infrastructure, and virtual boundaries are the contractual boundaries. Discussions on system boundaries for PED projects are found in a study by Lindholm et al. [19], with classifications autonomous, dynamic, and virtual. According to Vandevyvere et al. [10], virtual and dynamic PEDs will be the most common in cities and have the potential to act as a kind of battery for the larger grid. It is also mentioned that particularly virtual and dynamic PEDs might facilitate the transition from individual configurations, such as individual PVs, EV, or heat pumps, to collective integrated properties such as micro-grids, RE generation, and shared or collective housing and mobility solutions. Dynamic and virtual PEDs are proposed to be prioritized over autonomous, especially in areas that have dense populations, limited space, and availability of RES [7]. Laitinen et al. [35] have found that when a district becomes less self-sufficient, i.e., less need for energy storage, the life cycle cost can decrease dramatically. A conclusion from their study is that from an economical and technical perspective, it might be better to aim for a virtual or dynamic PED rather than a fully self-sufficient area. Such categorization of district system boundaries might be advantageous and provide a more clear and easy understanding of how to define boundaries, easier to modify projects according to the categories, and also evaluate and compare results from projects.

One interviewee (U2) discussed the benefits of geographical system boundaries with different scales suitable for various functions and activities. U2 thought that residential areas are the optimal size for citizen initiatives and engagement since they are small enough for solidarity, responsibility, and sharing energy. Two interviewees from utilities (U2 and U3) consider a larger perspective, such as city, municipality or regional, more appropriate than district-scale. One of the two interviewees (U2) thought that DH should be large-scale and not limited to districts, since one of the reasons for the DH installation in Sweden was to get rid of local wood- and oil-burning stoves in buildings. Thus, he thought that going back to small-scale systems might undo the work of phasing out local, fossil-based heat sources. This demonstrates the need for holistic planning during the initial stages of the PED, district heating should be discussed as a potential heat source to find the optimal solution for the energy systems.

An interviewee from the municipality (M3) discussed challenges with a city's size, which raises the question of how to interpret "district-scale". An example was that a district in a large city could be similar in size to an entire city in northern Sweden. He mentioned that even though it would be better to focus on districts with geographical boundaries in specific cases, it might not be possible to reduce smaller cities further due to their relatively small size. M3 raised concern on how to decide the system boundary if the entire city will be a PED. One argument he made was that it might be better to define a smaller area as a PED that can support other districts with higher energy consumption and identify areas that have a high potential for local RE production. That way, areas with high energy demand could benefit from the surplus RE exported from the PED and the overall impact in the city will be reduced. Moreover, M3 said that starting with a smaller area could be easier than aiming for a city-wide positive area since it might be easier to initiate a PED in a small area, which then will lead to more projects starting and thus benefitting the entire city. Furthermore, districts in cities differ greatly in terms of population density, energy demand, availability of local RE production [19], resources, energy infrastructure, and services [36], and thus some areas might be more suitable for being a PED rather than the entire city. A methodology for the identification of PED boundary conditions in cities based on GIS software and multi-criteria analysis is proposed in [36], with a focus on the macro-scale. The visual results demonstrated the optimal placement of a positive district in the city.

A few interviewees discussed issues and difficulties to determine the energy balance in the district. No specifics on the calculation of emissions or energy use are proposed in the white paper [5]. Thus, Sweden and other countries need to find a suitable, national framework for system boundaries and calculation for energy and emissions.

System boundary issues might be reduced if there are more insights and opportunities during the planning stages of PED. One solution is that cities and city districts could aim for an energy balance that suits their conditions. Thus, by choosing a suitable PED definition (such as dynamic, autonomous, or virtual [19] and a suitable energy balance concept for a district-sized project [4], system boundary problems might be reduced. Interview results showed that practitioners have different positions on system boundaries and what to be included. Further studies on system boundaries and how to include energy and emissions in the calculations are needed, since it is important for a district's potential to become a PED.

4.2.5. Stakeholder Involvement and Resistance

The importance of citizen involvement was a shared view among several interviewees. One interviewee mentioned that district-scale projects are ideal for citizen initiatives since districts are of optimal size for engaging residents, which is similar to the conclusion in [1]. However, five interviewees (M1, M3, M5, O1, and O2) considered stakeholder involvement a major challenge for PED projects. One interviewee (O2) thinks that it should be an initial starting point when dealing with challenges:

"It is about citizen engagement, a bottom-up perspective, breaking down any existing resistance and instead directing the citizens to get them committed".

Interviewee O2 is of the opinion that stakeholder involvement is an obvious requirement for successful projects. Several studies suggest that citizen engagement is vital for the transition towards sustainable cities [5]. In [7], it is mentioned that a strong engagement of residents and good cooperation between stakeholders are success factors for the implemented PEDs in Europe. However, consequences of behavior change due to economic factors might lead to greenwashing and inequal and excluding districts [37] and are drawbacks that need to be considered in PEDs. It might be beneficial to involve the public in PED projects with tools such as gamification, hackathons, and citizen observatories [20], thus limiting the economic motivator. An increased commitment among actors and knowledge of possible benefits might aid citizen engagement in Sweden and improve local initiatives.

The PED-related project M2 was involved with had a competitive selling process of the land to involve actors to develop high-quality projects. Various themes were used to generate innovative solutions within several topics, one example was the best solutions for water use. The winners were chosen based on the best content in their proposal and not on financial bidding. This approach suggests that competition within the market might lead to innovative ideas that strive for optimal and holistic solutions and are not based solely on an economic perspective. It may be a suitable approach for the involvement of actors: competitive processes and continuously raising the minimum requirement to improve the quality of solutions.

Resistance from stakeholders was considered a major challenge by four interviewees (M1, M5, O1, and O2), and two interviewees mentioned that reluctance to try new solutions was a challenge in their respective PED-related projects. Two interviewees (M1 and O2) reported initial resistance from the energy companies and one of them (M1) mentioned that the reluctance may be due to legislative issues. M1 mentioned that the energy companies were initially reluctant towards their project and one of the concerns of the energy companies was that the technical solutions may be too expensive. However, that concern was mitigated by clarifying the potential economic advantages. The other interviewee (O2) mentioned that the resistance from energy companies was reduced through meetings, and creating an interest in the project by convincing them that it is the right path towards a sustainable future. This indicates that communication and transparency could increase understanding and collaboration in such projects.

When asked about the initial reluctance from energy companies, one interviewee from the utility (U1) mentioned it is a traditional industry and might be perceived as reactive with a defensive approach rather than proactive. Another interviewee (U2) mentioned that energy production and distribution is a traditional business that may be less receptive to innovations. He also mentioned that it is important to engage with complicated issues and influence them for the better. Further, two interviewees (U2 and U3) thought that the negativity perceived by energy utilities might rather be vigilance on issues that emerge during projects such as legal and safety issues. One interviewee (U3) stated that when energy companies ask critical questions during projects it should not be misinterpreted as their reluctance toward innovative projects. Instead, it is due to their intention to do things carefully.

4.3. Major Facilitators/Benefits for PED

Improving collaboration, integrated innovative technology and political support are two aspects that many interviewees agreed on as major facilitators for PED projects. Important groundwork for future PEDs focus on climate change, financing/business models, and high ambitions where facilitators that more than two interviewees considered important. The interviewees' opinions on PED facilitators are shown in Figure 3. The interviewees had more scattered discussions on PED facilitators as compared to challenges.

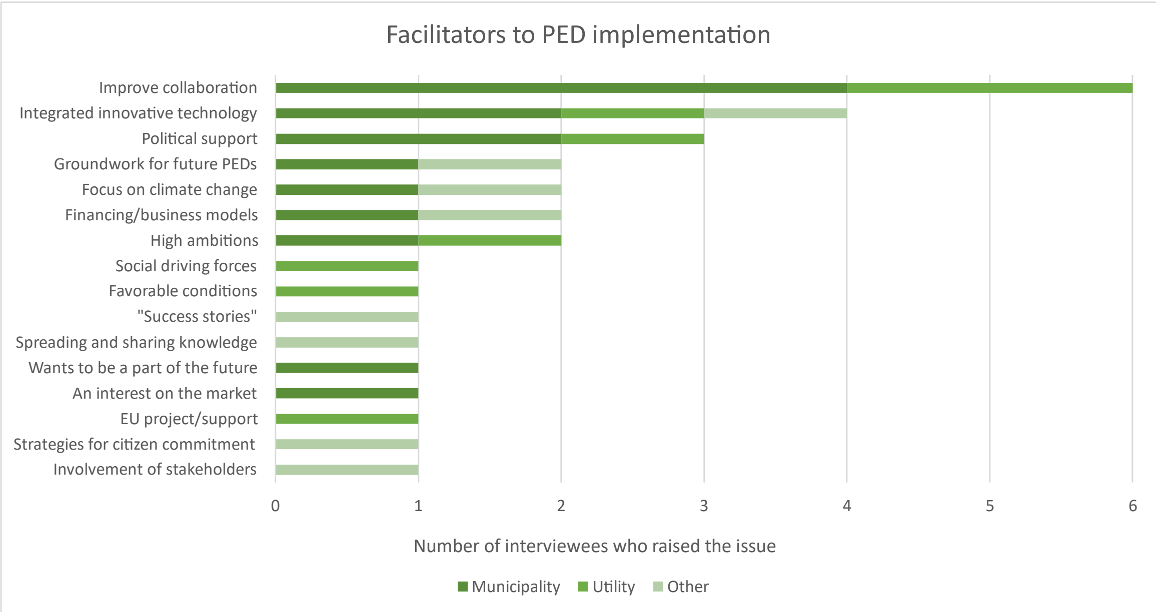

Figure 3. Interviewees' responses to facilitators to PED implementation were ordered based on their affiliation.

As compared to challenges, the interviewees discussed only briefly facilitators for PED. This may be because most PED projects are not completed yet and it might be easier to observe facilitators for PED when the project is in operation. On the other hand, challenges might be more visible during the planning and implementation stages. Further analysis of reported facilitators from completed projects may reveal additional information on the facilitators.

4.3.1. Improve Collaboration

The two interviewees from the same municipality (M4 and M5) mentioned that the PED-related project was an opportunity to improve the cross-disciplinary collaboration between sectors at the city office. The collaboration increases knowledge sharing and is also beneficial for other projects besides the current PED-related project they are working with. Another interviewee (M2) mentioned that to avoid challenges with process innovation in the PED-related project, a separate office was initially created to handle the city planning, with people from different departments. Two interviewees (U1 and U3) mentioned that different goals within work groups might be an issue and proposed that creating a common picture of what should be conducted could solve that problem.

4.3.2. Integrated Innovative Technology

When asked to reflect on the possible technical benefits of PEDs, two interviewees (M1 and U3) mentioned that an increased flexibility and energy exchange in a district would lower the area's electricity import demand. Accordingly, network/capacity expansion could be avoided. One interviewee (M1) argued that even though the new systems will have added costs, in the end, there might be some economic savings due to similar reasons.

He mentioned that it is important to understand all aspects of the system to learn and realize the advantages. It has been found that sharing energy locally would increase energy flexibility in the area, and districts could be more resilient to peaks and less dependent on larger systems [5]. Moreover, a broad range of technical solutions is more effective when several different RE sources are present [7].

4.3.3. Political Support

Three interviewees (M1, M4, and U1) thought political support was a facilitator for PED, and one of them thought it was the most important aspect of their project (M4). The interviewee (U1) involved with the large EU-funded project mentioned being an EU project had a signal effect, and that the regional political support for the project has been clear in various contexts. U3 mentioned that there is enthusiasm to find innovative solutions and contribute to climate change mitigation. M3 stated the importance for municipalities and companies to find their future role in climate and energy work and gain knowledge within different areas and sectors.

Several interviewees mentioned the influence of the EU and other international organizations to create solutions to mitigate climate change and related issues, which would aid sustainability projects. For example, one of the interviewees (M1) said:

"The political winds are definitely guiding in the right direction, even the old Swedish electricity law is analyzed from all directions, to facilitate for new systems, new actors".

According to two interviewees (M3 and U3), there is a big interest and enthusiasm in the market to develop solutions for climate change mitigation. One interviewee (O2) stated that even though their project had no political support, they benefitted from the climate change efforts and climate policies such as support for charging infrastructures.

M2 stated that the ambitious objective to become a European role model and build a sustainable city district was the main facilitator for their project. Further, according to him, great ambitions could attract other stakeholders and improve the process of sustainability projects. Another interviewee (M3) mentioned that national connections with other cities have facilitated generating interest among actors.

One interviewee (U1) discussed social stimulants and how they are contributing to societal development. Their project has been developing an innovation based on the idea of "gamification". The goal was to involve residents without them getting paid and create an interest and attention to climate change. Based on the user's individual situation, the residents receive tips and ideas to reduce their climate impact. A holistic view, which is highlighted in the PED definition, includes social aspects [5], social issues [1], and a just transition [38], which illustrates the need for improved efforts to include citizens. Nudging activities such as gamification could initiate peoples' thoughts and actions without compromising much on their comfort.

4.3.4. Groundwork for Future PEDs

A few interviewees noticed that even though there is not a pronounced PED aspiration in the city or organization, current ambitions and initiatives towards sustainability are similar to the PED definition. Two interviewees mentioned that there is a large interest in sustainable projects and M3 stated:

"We see that all the components that should be in a PED are what we want to develop in our city districts".

According to M3, one path to initiate PED projects in cities could be to begin with smaller components for a PED. An example he gave was to start with an efficient parking hub, which is highly relevant since the number of EVs will increase within the coming years, replacing fossil fuel-driven vehicles [19]. The surplus energy in a PED could cover parts of the increased electricity demand, supporting electric mobility in the district and other areas [19]. Thus, starting with subcomponents and then adding them all up could be one way to initiate PEDs.

4.4. Replication

Replication of city projects is very complex and requires adaptation to each city's specific situation and goal [9]. The following themes were discussed on replication of PEDs.

4.4.1. Sharing Knowledge

Two interviewees mentioned that their respective organization is developing replication models, methodologies based on knowledge and experiences. The organizations are leading two different PED-related projects that are in operation. One of them has created a checklist based on earlier experiences which includes stakeholder involvement, business models, political support, and documentation. The other project has created a model for citizen commitment, with easily accessible information from earlier projects. Another PED-related project, which is in the design phase, shares knowledge with others. A third project, in a newly built area, is focusing on creating opportunities and testing solutions partially or completely replicable to the existing city.

All except one thought the solutions in their PED-related projects could be replicated elsewhere. The deviating response was that knowledge and experiences are replicable but not specific solutions. Two interviewees (M4 and M5), involved in the same PED-related project, reflected on replicable components in projects, and M4 said:

"It is the work that is interesting, not the single component . . . but rather the thoughts of the work, how we advertise in the city . . . what we learn on the road".

4.4.2. Facilitators

When asked about facilitators for replication, four interviewees reported that transparency of results and proper evaluation are important. Three out of those four respondents were from municipalities. This finding is similar to that reported in [39] wherein proper evaluation possibilities and transparency of experiences and lessons were listed as drivers for replication. Other important aspects mentioned during the interviews on facilitators for replication were sharing knowledge and availability of funding. One interviewee (U3) argued that a clear aim, in the beginning, was important for evaluating the project and understanding if the work has contributed to the solution.

4.4.3. Challenges

Reflections on challenges for replication varied more than on opportunities. However, four challenges were considered central by more than one interviewee: too expensive solutions, conservatism within several sectors (such as the building sector), not being ambitious enough, and the need for someone to take the lead. Further, additional challenges mentioned by a few of the interviewees for replication were being too complicated work, getting the residents committed, a locking effect, and a risk for green washing.

One interviewee (U2) discussed the benefits of both a broad and narrow PED definition. He thought it might be better to have a narrow definition for pilot projects and a broader definition for replication to other districts and cities. An example was that perhaps only some of the solutions tested in a PED are suitable for replication to existing, old areas, and each project should choose the solutions fit for their situation.

4.4.4. Leading Replication

Interviewees had diverse opinions on actors who are most suitable for driving and leading the replication of PEDs. Overall, there was no single actor perceived to be ideal, and the interviewees think several companies and organizations can play a role in replication with different responsibilities and experiences. It was mentioned that the complexity of PED, as well as replication, would be simplified if different stakeholders such as municipalities, utilities, and companies, collaborated and shared knowledge and responsibilities.

One interviewee from a municipality (M1) thought the city could lead the replication of PED projects. This is because he mentioned that there are no competitive conditions between cities, and they usually work in the same network and together with various topics such as environmental issues and water and sewage treatment. He discussed that cities know the industries and have good connections, and it is good that they have local independence with a decisive role in climate plans. Another interviewee from utility (U1) argued that cities as leaders could bring legitimacy to the project.

5. Conclusions

PED is a recent concept and there is ambiguity on many facets of PEDs. Harnessing experiences is vital for comprehending the complexity of positive energy districts and it is important to study PEDs as well as PED-like projects since they hold valuable knowledge and experiences that might help to make cities climate friendly.

This paper provides perspectives of actors involved in PED-related projects on the opportunities and challenges that PEDs are facing. The study is based on interviews with professionals in Sweden who have relevant experiences. The small sample size and representativeness is a limitation to generalizing the study results. Further, the individual's responses may be biased based on their experiences from the respective projects. Nevertheless, the study put forward perspectives of actors in the PED domain which could be useful in realizing the PED ambition of Europe.

The seven projects that are discussed in this study do not meet the PED definition. Further, none of the projects started with an ambition to become a PED. Nevertheless, these projects have characteristics to become PEDs. It is reported that the cities' sustainability ambitions and initiatives have similarities with the PED definition and are in line with what stakeholders strive to develop in their city districts. The interviewees raised several challenges and benefits of PEDs. The interviews highlighted the importance of agreeing upon a definition that should consider the regional context while serving the overall purpose of PEDs. For example, several interviewees consider the "positive energy" and "annual surplus" terminologies in the PED definition may be unsuitable for Swedish conditions. According to them, such terminologies need adaptation based on specific climates and situations. Shorter timeframes such as monthly or seasonal might be more suitable; however, there are still uncertainties on which is ideal and how it will affect the project such as sizing of the infrastructure, land use, and magnitude of local RE production.

Municipalities/cities are mentioned as potentially suitable leaders for PED projects, while the contributions from academia, utilities, real estate companies, landowners, and NGOs are also reported to be important. Both a top-down and a bottom-up leadership structure have advantages; however, the majority of the interviewees think a top-down structure is preferable for PEDs. Nevertheless, most interviewees agreed on the importance of involving residents, and innovative approaches may be used to engage residents. For example, one interviewee from the municipality informed us about the selling of land based on the quality of the project application has resulted in innovative ideas from the market actors for their project. The results from the study suggest that stakeholder resistance towards PED could be resolved with communication and transparency which might increase collaboration in such projects.

The commonly reported challenges for PEDs were local energy production and energy flexibility regulations/legislation, sub-optimization issues, defining appropriate system boundaries, and stakeholder involvement. Interviewees stated that in pursuit of PEDs, it is important to keep a holistic view so as to avoid negative consequences from a larger system perspective. The majority of the interviewees thought that there were regulations that restricted the planning and development of PEDs, and most thought that system boundaries and stakeholder involvement were major challenges. A few aspects of system boundaries that were mentioned during interviews were to separate heat and electricity in energy balances, how large the district should be, and which activities and facilities should be included when calculating energy use and emissions. These aspects require further study.

Even though the interviewees' responses on facilitators varied more compared to the opinions on challenges, they listed several factors. Most of the interviewees were of the opinion that PEDs facilitated collaboration. Integrated innovative technology and political support were considered important facilitators by four and three interviewees, respectively. According to a few interviewees PEDs could result in important groundwork for future projects and focus on climate change. Replication of PEDs benefits from measures such as transparency of results and proper evaluation. This result also aligns with identified driving forces for replication in the literature. Sharing knowledge, economic benefits easily implemented systems and ideas, and projects having a positive effect on climate are also factors discussed for the replication of PED.

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