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Network dynamics of positive energy districts: a coevolutionary business ecosystem analysis

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Introduction: Amid the rising interest in sustainable urban development, Positive Energy Districts (PEDs) have become a focus of research. This study examines the dynamic processes that influence the development and scalability of PEDs from a co-evolutionary business ecosystem perspective.

Methods: To delve into the dynamics of Positive Energy Districts, we applied the business ecosystem framework to a real-world case study, namely the Hunziker Areal. Our research methodology involved the development and validation of a high-level conceptual model. This was achieved through workshops and guided interviews with experts engaged in pilot and research projects related to PEDs.

Results: The study highlights the significance of employing a systemic approach to evaluate the potential of PEDs in enhancing housing sustainability while creating value for diverse stakeholders. Through the utilization of causal loop diagrams, key feedback loops explaining the diffusion of PEDs are identified. Moreover, the study reveals varying perceptions of PED utility among stakeholders, who assess the impact using different Key Performance Indicators (KPIs) such as CO2 target achievement and well-being. Key factors influencing technology adoption, such as low prosumer electricity unit cost, are also identified.

Discussion: Our findings further shed light on crucial aspects affecting value capture and the attractiveness of the ecosystem to investors. Additionally, the study underscores the critical role of supportive policies and regulations in facilitating the diffusion and scalability of Positive Energy Districts.

KEYWORDS

Positive Energy District, business ecosystem, value network, resource pool, system dynamics

1 Introduction

Buildings account for approximately 40% of the EU's energy consumption and 36% of energy-related greenhouse gas emissions (European Commission, 2020). Achieving sustainability in the housing sector is therefore crucial to reaching sustainability goals. Positive Energy Districts (PEDs) are key stepping-stones of the European strategic plan that aims to boost energy efficiency and reducing CO_2 emissions of districts and buildings (European Commission, 2018a). According to Gollner (2018) a PED can be defined as: "energy-efficient and flexible urban areas or interconnected groups of buildings that produce net zero greenhouse gas emissions and actively manage local or regional surplus annual renewable energy production. They require the integration of different systems and infrastructures and the interaction between buildings, users and the regional energy, mobility, and information technology, ensuring energy supply and good living for all in line with social, economic, and environmental sustainability."

According to recent synthesis of European PED and related concepts (Bossi et al., 2020; Zhang, 2023) a large amount of PEDs are currently still in the development stage, commonly financed with private and public money usually through national and European grants under the framework of pilot and demonstration projects (Fatima et al., 2023). These studies emphasize the lack of appropriate business models and funding schemes as one of the most frequent challenge in the implementation of PEDs; conversely the existence of such schemes is one of the most frequently cited success factors. For example, the European Commission (EU) identified business models as an important determinant for the successful rollout of PEDs (European Commission, 2018b).

However, as argued by Mihailova et al. (2022) PEDs are often constituted by a group of several stakeholders with different roles that follow a common goal. Therefore, we need to expand the analysis beyond the traditional business model view, which looks only within firm boundaries, and adopt an ecosystem view in order to achieve systemic change (Speich and Ulli-Beer, 2023).

As part of the PED COST Action,[1] our research aims at assessing upscaling prospects of PED and PED-related concepts in Switzerland, where several PED-related concepts have emerged but are not yet widely implemented. We consider distinct socio-economic, technical, structural, and regulatory conditions from a business perspective. To this aim, we use a conceptual model to explain the adoption and scalability of PED, applying the ecosystem lens as developed by Speich and Ulli-Beer (2023).

The goal of this work is to answer the following research questions:

- Which dynamic factors affect the development of the Positive Energy District Business ecosystem
- Which barriers and opportunities influence these dynamics in the Swiss context

Answers to these research questions were sought by analyzing the PEDs business ecosystem of selected case studies to understand the interaction between actors, resources, and their contextual environment, and by developing a conceptual model that captures the endogenous and exogenous dynamics of PEDs development.

The conceptual model was represented in a Causal Loop Diagram (CLD) to show the dynamic interaction among the different variables such as investment decisions, network effects, evolution of techno-economic and societal metrics. In our mapping, we are also considering external influences from the business environment such as energy and technology prices as identified using a PESTLE analysis.

1 The COST Action Positive Energy Districts European Network (PED-EU-NET) aims to mobilize researchers and other relevant stakeholders across different domains and sectors to drive the deployment of Positive Energy Districts (PEDs) in Europe through open sharing of knowledge, exchange of ideas, pooling of resources, experimentation of new methods and co-creation of novel solutions.

This article is structured as follows: we begin by reviewing existing literature on business models for energy communities and the concept of the business ecosystem (Section 2). We then introduce our methodology, including the description of the ecosystem framework for our theoretical analysis (Section 3). In Section 4, we apply the ecosystem framework to a PED case study and depict the development of the conceptual model, which is validated in workshops and interviews. The causal loop diagrams serve as focal points for our analysis and discussion on the dynamics affecting the development of PEDs (Section 4.3). Finally, Section 5 gives a summary and an outlook for further research.

2 Literature review

2.1 Business models for energy communities and the business ecosystem framework

In Switzerland, the new Climate and Innovation Act includes the goal of achieving net-zero greenhouse gas emissions by 2050. The achievement of the net-zero target will be dependent on a significant and rapid reduction in domestic greenhouse gas emissions (SWI, 2023).

The PEDs and other related concepts are becoming increasingly important to achieve the goal of zero emissions, as it ideally considers not only the generation of local renewable electricity, but also the retrofitting of buildings to reduce energy demand, the electrification of heating and transport, the expansion of shared mobility, and the use of intelligent algorithms to increase efficiency and flexibility (Nguyen and Batel, 2021; Eicker, 2022).

Therefore, there is a need for supporting business models that address the different dimensions of PEDs: Renewable energy generation, energy efficiency, sustainable mobility, and building refurbishment (Bossi et al., 2020; Zhang, 2023).

Recent studies concentrate on analyzing business models for energy communities. Kubli and Puranik (2023) compiled several business model typologies with the aim to help practitioners and researchers in the design of business models suitable for their own energy community. Furthermore, Konstantinou and Haase (2023) highlight six business model archetypes for building renovations at district level, entailing energy efficiency and renewable energies. Other reports, resulting from European research projects, have focused on describing business models for building refurbishment (Laffont-Eloire et al., 2019; Krosse et al., 2021; Bagaini et al., 2022; Bianco et al., 2022). Additionally, the business models for sustainable mobility have also been studied (Cohen and Kietzmann, 2014; Boer et al., 2022).

However, the business model perspective typically focuses on the individual firm's perspective. This perspective is often insufficient to achieve system-level changes (Bolton and Hannon, 2016; Manninen et al., 2018; Speich and Ulli-Beer, 2023). In addition, PEDs are often a result of a partnership between different stakeholders who work together toward a common goal and, as a result, create environmental, ecological and economical value (Mihailova et al., 2022). Therefore, the ecosystem perspective seems to be more adequate to assess PEDs.

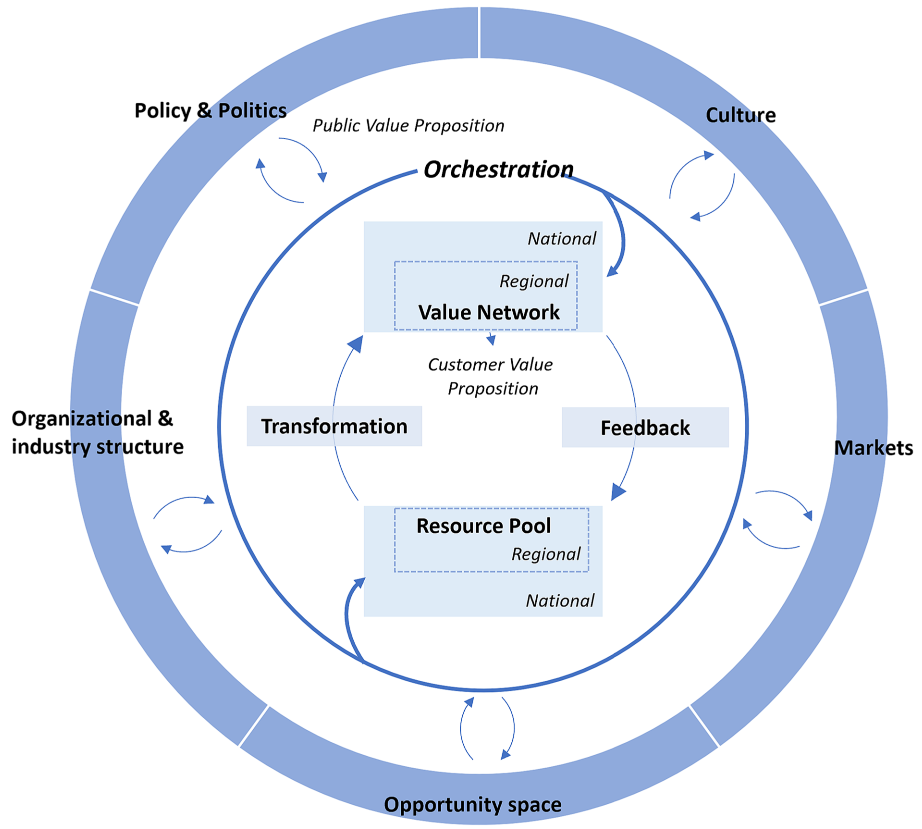

FIGURE 1
Co-evolutionary business ecosystem perspective (Speich and Ulli-Beer, 2023).

The ecosystem metaphor was derived from biology and introduced in the business environment by Moore (2006), who defines the Business Ecosystem as an economic community of actors that interact and co-evolve with each other and with their environment.

To analyze the business ecosystem dynamics under low-carbon transitions, Speich and Ulli-Beer (2023) developed a Co-Evolutionary Business Ecosystem Perspective (CEBEP, Figure 1). This framework provides a conceptual explanation of how actors within the value network should align to work toward a common goal. Critical activities are the Orchestration of a common Resource Pool for the Value Network and the collaboration with the surrounding Business Environment (e.g., with Policy and Politics). The transformational results are business model innovations and a more effective and efficient use of resources, and finally, a competitive Value Network for serving customer with sustainable value propositions supporting public interest.

2.2 System dynamics and the positive energy district ecosystem

The dynamic evolution of the Positive Energy Business Ecosystems presented in section 2.1 is studied using system dynamics. System dynamics (SD) is a methodology combining graphical representation and mathematical modeling to understand the structure and behavior of complex systems over time (Sterman, 2000). This methodology facilitates the assessment of business strategy over time and helps to understand how business performance can be influenced (Warren, 1999).

System dynamics builds on CLDs, these are compelling analytical tools that visually represent the key variables and the connections between them. Through the use of arrows and feedback loops, CLDs intuitively illustrate the positive or negative impact between variables as well as the driving and balancing forces within a system (Lin et al., 2020; Paasi et al., 2023).

The literature regarding the use of system dynamics to assess different dimensions of PED is extensive. For instance, several authors assess the impact of the transformation of the building sector on the total energy demand, evaluating the effectiveness of different policies and regulations (Müller and Ulli-Beer, 2010; Onat et al., 2014; Zhou et al., 2020). Additionally, the work of Gómez Vilchez and Jochem (2019) gives a complete overview of SD models that study the adoption of electric and hybrid vehicles. Moreover, some work has been done on the adoption of smart meters (Dehdarian, 2018) and the expected behavioral change associated to it (Ricci, 2013).

System Dynamics has been used to study several aspects concerning sustainable business model strategies. Abdelkafi and Täuscher (2016) developed a generic model to represent the dynamics of business model for sustainability. Other authors focused on the evaluation of business model strategies for prosumer communities and flexibility valorization (Zapata Riveros et al., 2019; Kubli and Canzi, 2021; Zapata Riveros et al., 2021). These publications focused on the classical concept of business models, whereas Paasi et al. (2023) introduce the use of CLD to describe innovation ecosystems.

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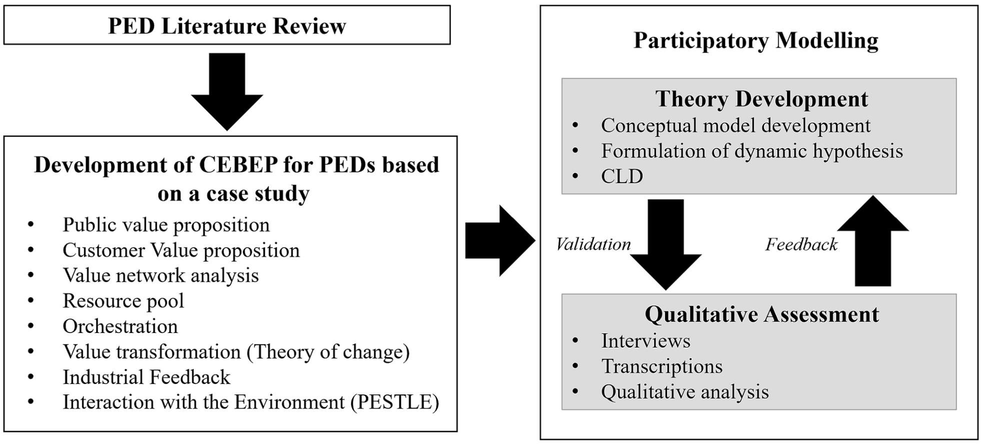

FIGURE 2
Research methodology.

We can conclude that SD is a powerful tool to study different characteristics related to PEDs; nevertheless, the previous studies usually concentrate on a specific dimension without considering the complementarities among them. Moreover, none of the reviewed papers have shown the different interrelations of business ecosystems for the development and scaling of PEDs.

3 Methodology

The methodology followed in this study is depicted in Figure 2. In the first phase, we conducted desk research regarding Positive Energy Districts. Based on the literature insights, we applied the CEBEP (Speich and Ulli-Beer, 2023) to structure the Positive Energy District ecosystem. Afterward, we used participatory modeling to identify the dynamic aspects of PEDs.

Using this combination of methods allowed the mapping of the business ecosystem actors, their mutual interactions, and their relationships with the environment. This facilitated the identification of feedback loops that explain the dynamic development of the PEDs and that were developed and validated through participatory modeling approaches.

3.1 Development of the co-evolutionary business ecosystem perspective for PEDs

The business ecosystem perspective (Speich and Ulli-Beer, 2023) was used to identify the characteristics of a PED ecosystem in a case study approach. To assess some of the ecosystem elements, we applied well-known tools and methodologies.

For instance, the value network analysis maps the value creation deliverables between stakeholders to identify and visualize the benefits that each stakeholder contributes to and receives from the project, considering not only the financial exchange but other kinds of values such as knowledge or intangible benefits. Outlining these value streams improve the understanding of each other's roles and responsibilities, as well as the benefits that are being created (Lewrick, 2022). In this way, stakeholders can work together more effectively to achieve common goals and create shared value (Mihailova et al., 2022).

The Resource Pool assessment entails the identification of resources that are accessible by all the stakeholders in the value network. These resources are classified into several categories, including physical resources, financial resources, data information and digital assets, social capital, intangible resources, and human resources and know-how (Speich and Ulli-Beer, 2023).

Furthermore, the value network transformation was analyzed based on the theory of change. This methodology has been extensively applied in social programs to assess impact. It gives an explanation of how an initiative (such as a project or a program) can lead to a change process (Claus and Belcher, 2020). Mattos et al. (2022) adopted the theory of change as a tool to assess circular business models. They argued that the Theory of change can help investors and other stakeholders by showing the path from resources to impact and give them a tool to not only evaluate financial resources but also assess environmental and social impact.

Additionally, to analyze the interactions with the environment, we employed a classic strategy tool: The PESTLE Analysis. PESTLE stands for Political, Economic, Social, Technological, Legal and Environmental factors. This tool helps decision makers identify external influences that affect an ecosystem (Lewrick, 2022).

We applied the Co-Evolutionary Business Ecosystem Perspective frameworks to the case study of the Hunziker areal, a PED settlement located in Zurich.

3.2 Participatory modeling

Participatory modeling refers to the involvement of stakeholders in the development of conceptual models. Engaging with the stakeholders facilitates the understanding of complex systems (Lee et al., 2022). In this work, we used the generic participatory modeling process framework developed in Ulli-Beer et al. (2017).

Based on the insights of the ecosystem framework, we developed a conceptual model to explain the drivers and barriers that affect the scalability of the PEDs. We identified endogenous variables and formulated the dynamic hypothesis. These were validated with stakeholders as explained in Section 4.2.1. Finally, we integrated the feedback of the interviews in the conceptual model resulting in a multi-dimensional causal loop diagram that is described in section 4.3.

The theory validation in this study was based on the grounded theory approach (Corbin and Strauss, 1990). It employed a combination of semi-structured interviews and a workshop to validate and refine the emerging theory. The interview participants were selected for their expertise in PED projects, the goal was to gather their standpoints, experiences, and insights (Refer to section 4.2.1 for details on the interviewees).

The qualitative content analysis began with the transcription of the interviews and the workshop discussion. Subsequently, the data obtained from the transcriptions were subjected to deductive coding. This entailed constructing a coding framework comprising predetermined categories related to barriers for the growth of PEDs, benefits for the community, orchestration, drivers for investors, and opportunities. Furthermore, during the coding process, new code words were introduced when new relevant topics emerged in the interviews that were not initially accounted for.

The coding process involved systematically assigning relevant codes to specific segments of the interview data, allowing for a structured analysis of the information. Finally, the coded data were synthesized and summarized to extract the main findings and insights. This involved reviewing and comparing the coded segments to identify common themes and patterns across the interviews. Axial mapping was used to identify interaction between codes that are mapped as relevant variables in the CLD.

4 Results

In the following subsections, the results of the three methodological phases are presented.

4.1 Development of CEBEP for PEDs- case study Hunziker areal

To explain the business ecosystem of PED concepts, we combined the CEBEP (Speich and Ulli-Beer, 2023) with the business ecosystem design principles described in Lewrick (2022).

The ecosystem of a PED largely depends on contextual aspects such as the geographic location, policies and regulations, among others. In this section, we aim to analyze the different elements of a Business ecosystem as shown in Figure 1 in relation to the PED concept. First, we explain what each of the Business Ecosystem Perspective elements represents for the PED concepts, and afterward, we will exemplify them using the Hunziker Areal as a case study.

The Hunziker Areal is situated in the north of Zurich; it is a pioneering settlement and development project. The areal is operated by the building cooperative “Mehr als Wohnen” (Translated from German: More than housing). It offers living space for about 1,200 people in 13 energy-efficient buildings and is a workplace for about 150 people. “Mehr als Wohnen” tries to respond to changing housing needs and social change by promoting community engagement and fostering a sense of community belonging, while promoting sustainable and socially cohesive living practices (Rohrbach, 2021).

One of the primary goals is to achieve the 2000-watt society goal (Lenel, 2012), which, among other measures, limits the primary energy use to 2000 Watt per person per year. In order to achieve this ambitious goal, important measures have been implemented, such as the construction of energy efficient buildings, the use of new energy technologies, and limitations on the use of cars (Blumer et al., 2021). The Hunziker Areal was selected as a case study due to its notoriety in Switzerland and the large amount of literature available.

4.1.1 Public value proposition

The PED concept is seen as a vision to guide local renewable energy transition. The public value proposition is to mitigate climate change by reducing the Green House Gas emissions of the whole community (Derkenbaeva et al., 2022). This is in line with the objectives of the city of Zurich, which was the first Swiss city to commit itself to the goals of the 2000-watt society in a referendum (City of Zurich, Office for Environmental and Health Protection UGZ, 2011).

4.1.2 Customer value proposition

PED provide three general value propositions to the customers: (1) affordable and reliable energy from local renewable resources (Derkenbaeva et al., 2022), (2) reducing energy poverty, as well as (3) addressing social aspects (Nguyen and Batel, 2021) such as justice and wellbeing.

Apart from the general customer value proposition, each PED has particular offers for their customers depending on the concrete business models. As mentioned in section 2.1, there exists a large variety of business models that cover distinct aspects of PEDs related to energy generation, sustainable mobility, and housing.

In the particular case of the Hunziker Areal, the customer value proposition is to provide a social and environmentally friendly place for living and working. This is achieved by using renewable energy, increasing energy efficiency, offering affordable living, and encouraging a participatory environment among the residents (Derkenbaeva et al., 2020).

4.1.3 Value network

Typical stakeholders in a PED value network are the municipality, service and product providers, utility companies, cooperatives, and the citizens. These stakeholders can play multiple roles within the ecosystem (Mihailova et al., 2022). For instance, the municipality can, in some cases, orchestrate and finance the development of a PED. Supplementary Figure 10 depicts the value network analysis of the Hunziker Areal.

4.1.4 Resource pool

In PEDs, physical resources refer to tangible resources such as energy infrastructure, renewable energy sources, and energy conversion and storage devices. Financial resources encompass investment capital, government incentives, and subsidies. Data information and digital assets refer to smart grid systems, data analytics, and energy management software. Human resources and know-how comprise the skills, knowledge, and experience that individuals bring to the projects, such as technical skills, problem-solving abilities, and expertise in specific industries or areas. In the context of PEDs an example of Social capital is the participation of residents in the co-creation process. Intangible resources refer to

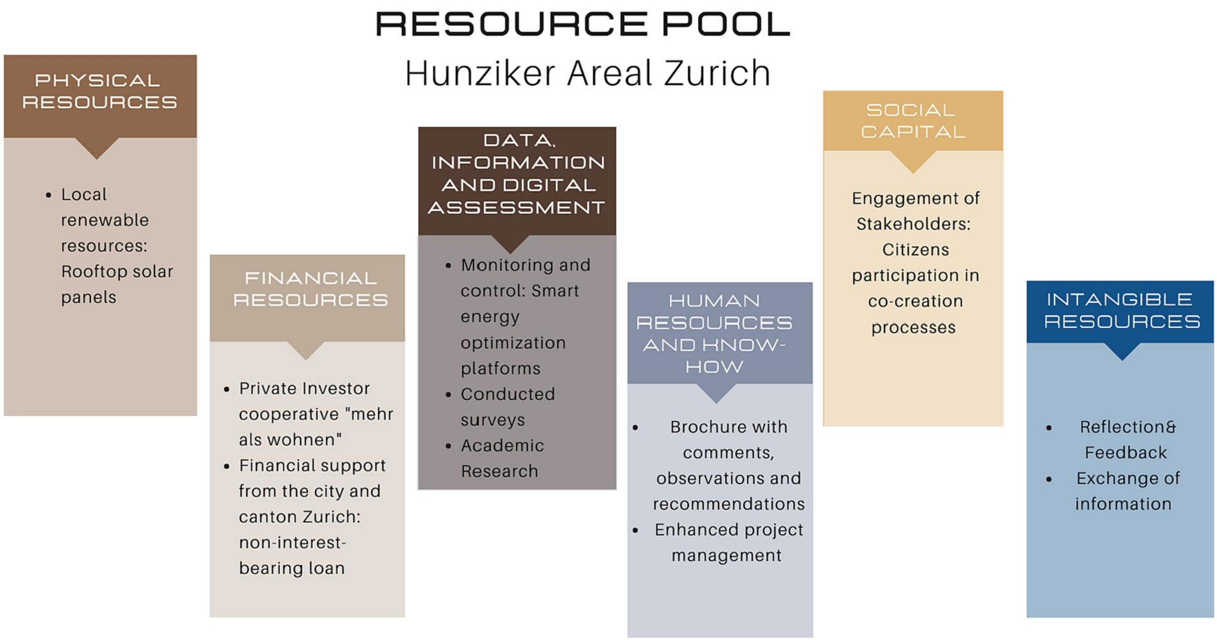

FIGURE 3
Resource pool of the Hunziker areal.

non-physical, abstract assets important for the success of an organization or community such as informal information exchange. Figure 3 illustrates the exemplary resource pool of the Hunziker Areal.

4.1.5 Orchestration

The orchestration is part of the ecosystem governance, the role of an orchestrator is to coordinate the activities among the ecosystem actors, i.e., the actors in the value network and the business environment (Lewrick, 2022; Paasi et al., 2023). The role of the orchestrator of a PED is usually played by the municipality, private companies or cooperatives that can involve private and public actors.

In the case of the Hunziker Areal, "Mehr als Wohnen" assumed the orchestrator role by aligning the interest of the different stakeholders such as the municipality, stakeholders with technical expertise, and residents of the community (Derkenbaeva et al., 2020).

4.1.6 Value network transformation

According to the literature, the transformation of the value network occurs through interaction with the associated resources (Speich and Ulli-Beer, 2023). As explained in section 3.1 we use the Theory of change to illustrate the transformation of the PED resources over the time. This approach involves a systematic examination of the inputs, outputs, outcomes, and impacts of the projects. Supplementary Figure 10 shows the Theory of change of the Hunziker Areal.

Where the impact of the project is the expected overarching societal benefit, the outputs are the concrete actions developed within the project that contribute to achieving the impact, and the outcomes go beyond the project, facilitating its replicability by helping to improve the efficiency of other projects.

4.1.7 Industrial feedback

Industrial feedback describes the strengthening of the resource pool through the activities of the value network. PEDs enhance the resource pool by augmenting the technology capacity. This attracts more companies to the ecosystem with the aim of offering complementary products and services, thus reinforcing the resource pool with complementary technologies.

Several examples of this effect can be found. For instance, by refurbishing buildings, a significant reduction in heat demand can be achieved, facilitating the installation of Heat pumps (HP).

4.1.8 Interaction with the environment

As stated in Section 3.1, the PESTLE analysis is a strategic tool suitable for analyzing the interaction of the ecosystem with its environment (Lewrick, 2022). Supplementary Table 2 illustrates the PESTLE analysis of the Hunzier Areal.

4.2 Theory development

Based on the insight from the Business ecosystem analysis of PEDs, we have developed a first visualization of the conceptual model, as illustrated in Figure 4. The graphic provides a high-level overview of the ecosystem activities. Multiple stakeholders, such as the project initiator, the orchestrator (or project manager) and the companies that belong to the business ecosystem (i.e., service and product providers), interact with each other and share the goal to develop a PED. Their activities enlarge the resource pool by expanding the knowledge and technology base, which might also attract new financial resources. Through this co-evolutionary process, new value propositions for customers and the ecosystem actors emerge, consequently enhancing the attractiveness of the ecosystem.

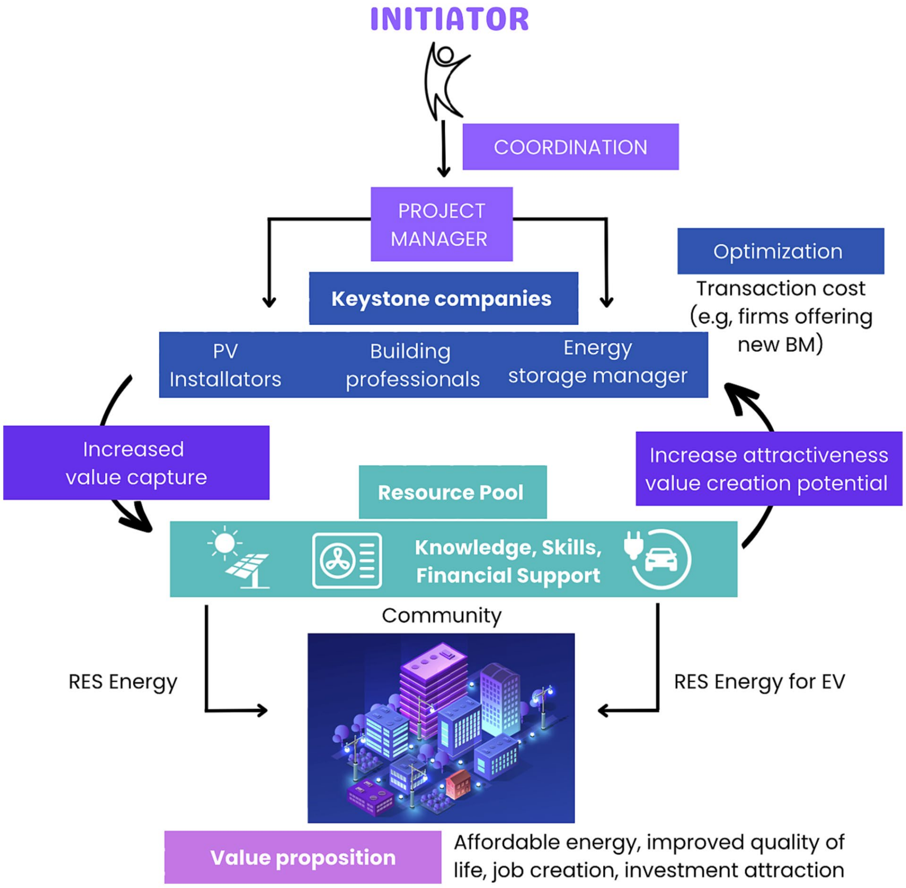

FIGURE 4
Conceptual model of the PED business ecosystem.

TABLE 1 Interviewed stakeholders.

Organization	Role	Code	Duration
2000-Watt-Areal (Switzerland)	Regional Manager	M_01	54 Min. 39 Sek.
Lugaggia Innovation Community (Switzerland)	Project Manager	M_02	55 Min. 30 Sek.
New Energy coalition (Netherlands)	Project Manager – Business models	M_03	36 Min
University of Geneve	Researcher – Social aspects	M_04	1 Std. 46 Min. 27 Sek. (Workshop)
University of applied science and art western Switzerland	Researcher – Technical aspects	M_05	

According to the previous description, we hypothesize that the development of the PED ecosystem follows a self-reinforcing mechanism. If there is no obstacle delaying these dynamics, entrepreneurs and investors should be willing to invest and scale the PEDs concept. Nevertheless, financing and scaling up are by now important challenges of PEDs (Bossi et al., 2020; Fatima et al., 2023). Therefore, we have performed expert interviews to examine our conceptual model and gain insight into its applicability. We focus on the following assumptions:

(1) Sharing of mutual beneficial resources reinforces the capacity of the keystone companies to offer value creation over time.
(2) There exist several factors that decrease the value capture capacity of the PED actors and, in this way, reduce their willingness to invest and participate in the Ecosystem.

4.2.1 Validation of the conceptual model of the PED business ecosystem – interview analysis

In total, 3 semi-structured interviews and a workshop were performed. Following the grounded theory methodology, the interview guidelines were adapted to dig on the previous finding and to meet the expertise of the different actors. To improve the quality of the interviews the guidelines were sent in advance to the interviewees.

We have interviewed individuals who have either participated in the development of positive energy district (PED) projects or are currently engaged in researching this concept, see Table 1 for further details.

4.2.2 Barriers for the growth of PEDs

One of the main factors we wanted to understand through the interviews was the barriers that impede the widespread

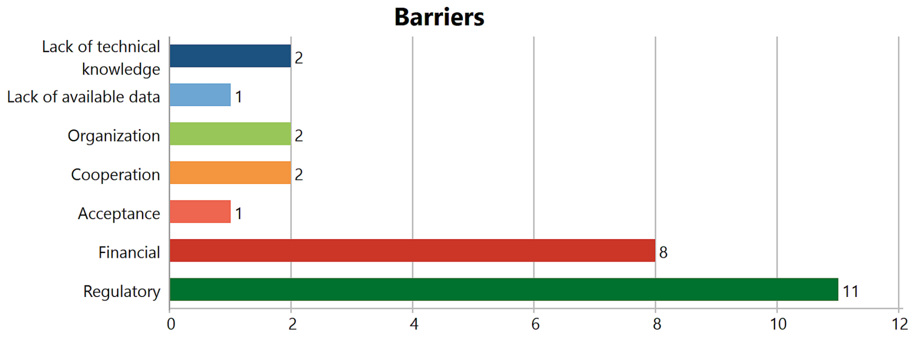

FIGURE 5
Main barriers for the growth of PEDs and frequency of their mentions (due to the small sample size, the number of mentions is only indicative of the topic's importance).

implementation of PEDs. Through the insights of our interviews, we identified different factors that limit success of PED initiatives (see Figure 5).

Among these challenges, it becomes evident that regulatory and financial factors play a preeminent role. When concretely asking about the orchestration challenges and their intrinsic transaction cost, most of the interviewees did not consider this to be an issue at the moment.

The interviewees often mentioned regulatory factors as significant barriers to innovative business models. For instance, they highlighted that the restrictive environment in Switzerland greatly affects the profitability of a PED project.

> *"Whereas, for example in Denmark there are a lot of companies that do business model just with batteries and they use batteries to do arbitrage and peak shaving. The market is very different. In Switzerland it is more conservative than in Europe. Policies and regulations are the main barrier" (M_02).*

Another aspect that was also mentioned was the limitations regarding heritage-protected buildings, which pose significant challenges in terms of energy renovations (M_03).

Furthermore, the interviewed actors mentioned that at this stage, where the technical feasibility of several technologies is being tested, it is important to perform lobbying activities, to inform policy makers about the need to adjust regulations in order to tap into the opportunities of PEDs.

Regarding financial barriers, respondents cited mainly the high up-front costs of the technologies, which in some cases cannot be recouped. This specially refers to large batteries and innovative technologies such as Building integrated photovoltaic systems (BIPV).

4.2.3 Drivers for investors

The insights of the interviews show that investors are primarily driven by three main factors.

Firstly, most of the interviewees agreed that the economic aspect is the most crucial one from the investors point of view. They always seek profitable opportunities (e.g., M_01. M04).

> *"I think for investors is still the money, the incentive. The return has to be right at the end of the day and that's whether institutional or whatever the investor is, that still drives everything" (Translated from M_01).*

Secondly, the growing recognition of the urgent need to address climate change is another significant driver. Investors are increasingly aware of the environmental challenges and the importance of transitioning toward low-carbon solutions (M_01). This aspect is particularly significant in projects where municipalities or other public institutions participate in the financing.

Lastly, investors in positive energy districts also recognize the value of fostering a sense of community for residents. They understand that these districts can create attractive living environments that promote well-being, social interaction, and a higher quality of life. This sense of community not only benefits residents but also contributes to the attractiveness and desirability of the district, which can positively impact property values and long-term sustainability (M_01).

4.2.4 Opportunities

Positive energy districts or energy communities offer a range of opportunities for sustainable development, as highlighted through the interviews. Currently, PEDs frequently serve as living labs, allowing for the testing of not just technology, but also innovative business concepts.

By integrating innovative technologies and smart grid solutions, positive energy districts open up new possibilities for innovative business models. These models can include for example the provision of services related to energy management, such as energy monitoring and optimization solutions.

> *"So, we created an energy community and we are operating it to understand and investigate what works, what does not, what are the technical limits, what are the opportunities, what kind of business model could exist and so on" (M_02).*

Furthermore, thanks to the highly supportive conditions of the pilot projects, which, for example, remove legal, administrative, and financial barriers, early stage technologies that have not reached market maturity can be tested to prove their technical reliability, thereby promoting their further development (M_03).

Additionally, the knowledge gained during the development of these living labs enhance the common resource pool and facilitate the replicability of the projects in other municipalities.

4.3 Description of the causal loop diagram

Recall that the goal of this research is to analyze the dynamic processes that affect the development of the Positive Energy District Business ecosystem. To this aim, we used the inputs of our interviews to further develop our conceptual model using the intuitive causal loop diagrams.

The development of a PED project is highly dependent on its contextual setting. Therefore, our challenge is to design a generic model that can be easily adapted to the particularities of each PED. Our CLDs capture the most important elements of the PED business ecosystem as explained in section 4.1. They describe how the PED ecosystem generates value for the different stakeholders, i.e., to the investors, the keystone companies and the residents of the PED. According to Mihailova et al. (2022) the investors of a PED can be municipalities, citizens, or private companies among others, whereas the keystone companies include firms providing products and services to the PED (e.g., photovoltaic installers).

The CLDs show which processes influence the resource pool development over time. In our case, the resource pool refers mainly to the available sustainable technologies. For simplicity reasons, we limited our analysis to the diffusion of renewable energy such as photovoltaics, heat pumps, and mobility solutions like electric vehicles. However, as explained in section 4.1.4, the resource pool of a PED encompasses not only the technology base but other tangible and intangible resources such as knowledge exchange and citizens engagement.

Furthermore, several endogenous variables in the CLDs reflect various key performance indicators that enable the assessment of public goals (e.g., CO_2 emission reduction, RES installed capacity etc.) and internal goals (e.g., Increased people satisfaction). The selected KPIs (see Supplementary Table 3) consider several dimensions of PEDs such as energy, environmental, mobility, economic, social and governance (Martinopoulos et al., 2021).

In the following section four different CLDs are presented which describe how utility evolves over the time for the different PED actors: investors, value network actors, residents and how regulatory barriers can hinder the PED uptake.

4.3.1 Perceived utility of the investor

The causal loop diagram presented in Figure 6, illustrates the parameters that influence the diffusion of renewable technologies, such as Photovoltaics, electric vehicles and heat pumps in PEDs. The different feedback loops are summarized in Supplementary Table 4. According to our interviewees, the diffusion of PEDs is directly linked to the economic benefits that the investors perceive.

The economic benefits of photovoltaic energy can be operationalized using the prosumer electricity unit cost (PEUC) developed by Pillai et al. (2014). The PEUC is estimated as shown in equation (1). It considers the investment cost of the Photovoltaic (PV) system I_0, the feed-in income R_{FIT}, the cost of the remaining electricity that cannot be covered by renewables C_{RD} and the total demand D.

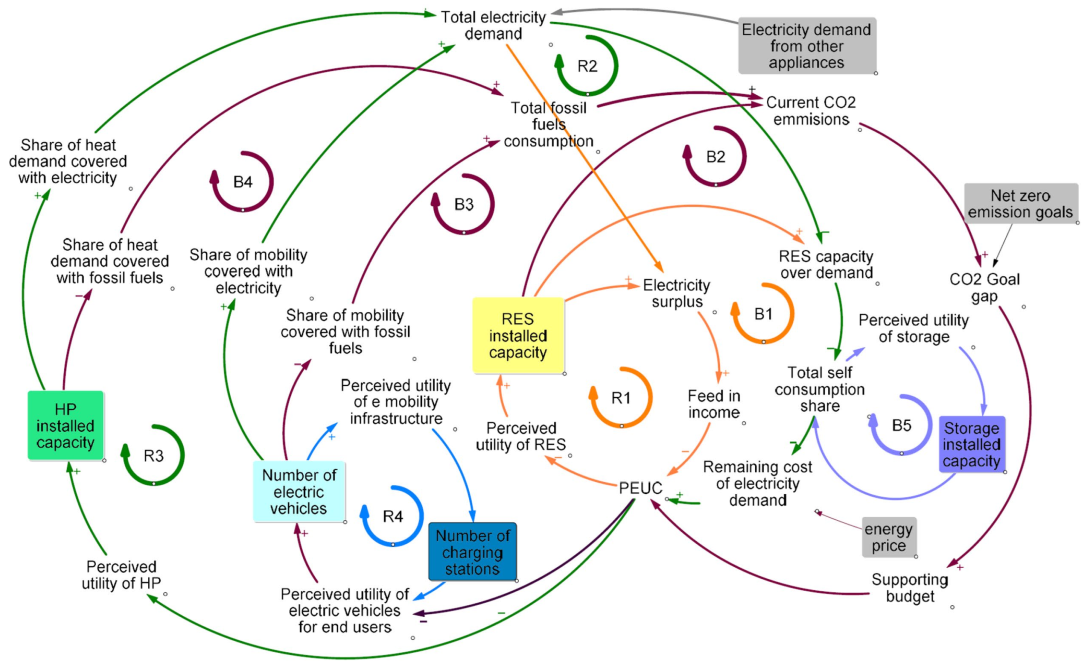

FIGURE 6
Diffusion of sustainable technologies in a PED. (HEW, Housing, Energy and Well-being; HP, Heat pump; PEUC, Prosumer Electricity Unit Cost; RES, Renewable energy resources; CO_2, Carbon dioxide).

$$\pi_p = \frac{I_0 - R_{FIT} + C_{RD}}{D} \quad (1)$$

If the PEUC is low, the financial attractiveness of the Renewable Energy system (RES) increases. Increasing the feed-in income by enlarging the capacity of renewables results in a further increase of PEUC and thus improves the perceived utility of renewables as reflected in the reinforcing loop (R1) "Increasing Utility of Renewables." This is partially compensated by the balancing loop (B1) which describes the negative effect that the additional installation of a PV has on the PV self-consumption share. As more PV is installed, the potential for generating surplus electricity, which might not be fully consumed on site, increases. This situation results in a decrease in the share of PV self-consumption, which translates into higher feed-in tariff revenues, but also an increase in the PEUC.

In order to reach the emission goals, the government can intervene by establishing supporting mechanisms, usually in form of financial support. These policy measures increase the attractiveness of sustainable technologies. By receiving this support, the diffusion of these technologies gradually increases and reduces CO_2 emissions toward the emission goal. As the emission goal becomes feasible, the supporting budget will be decreased; establishing the balancing loops "CO_2 Goal Achievement" (B2, B3, B4). Finally, the effect of installing electric storage is reflected in B5.

The PEUC not only influences the perceived utility of the renewable energy but also the utility of complementary technologies such as heat pumps and electric vehicles; also, the increase in the installed base of cheap and local renewable energy increases the attractiveness of these complementary technologies. This network effect is illustrated in the Reinforcing loops "Lower PEUC boosts e-mobility adoption" (R2) and "Lower PEUC boosts HP installation" (R3).

Apart from the electricity price, the perceived utility of electric vehicles is highly dependent on the available charging infrastructure. As mentioned in the interviews, this is a typical causality dilemma: installing charging stations is attractive when there are enough electric cars on site and vice versa (R4).

We regard the installed capacity of smart meters as an external variable because this is part of the Swiss Energy Strategy 2050, and thus the smart meters roll-out is mandatory for energy utilities (BFE, 2015).

4.3.2 Perceived utility of value network

The CLD presented in Figure 7 describes the effects of the industrial feedback as described in section 4.1.7. From an economic perspective, one of the goals of PEDs is to provide opportunities for companies to offer products/services from different sectors (Mihailova et al., 2022).

According to Abdelkafi and Täuscher (2016), the value creation capacity, the value created to the customer, and the value captured can reinforce each other in a positive feedback loop. In general, the value creation capacity is related to the availability of key resources and process to create value (Abdelkafi and Täuscher, 2016). In the case of PEDs, the key resources comprise, for example, sustainable technologies, such as photovoltaic panels, smart meters, and heat pumps.

The effect of reinforcing the resource pool by expanding the installed base of these technologies is twofold: on the one hand, it

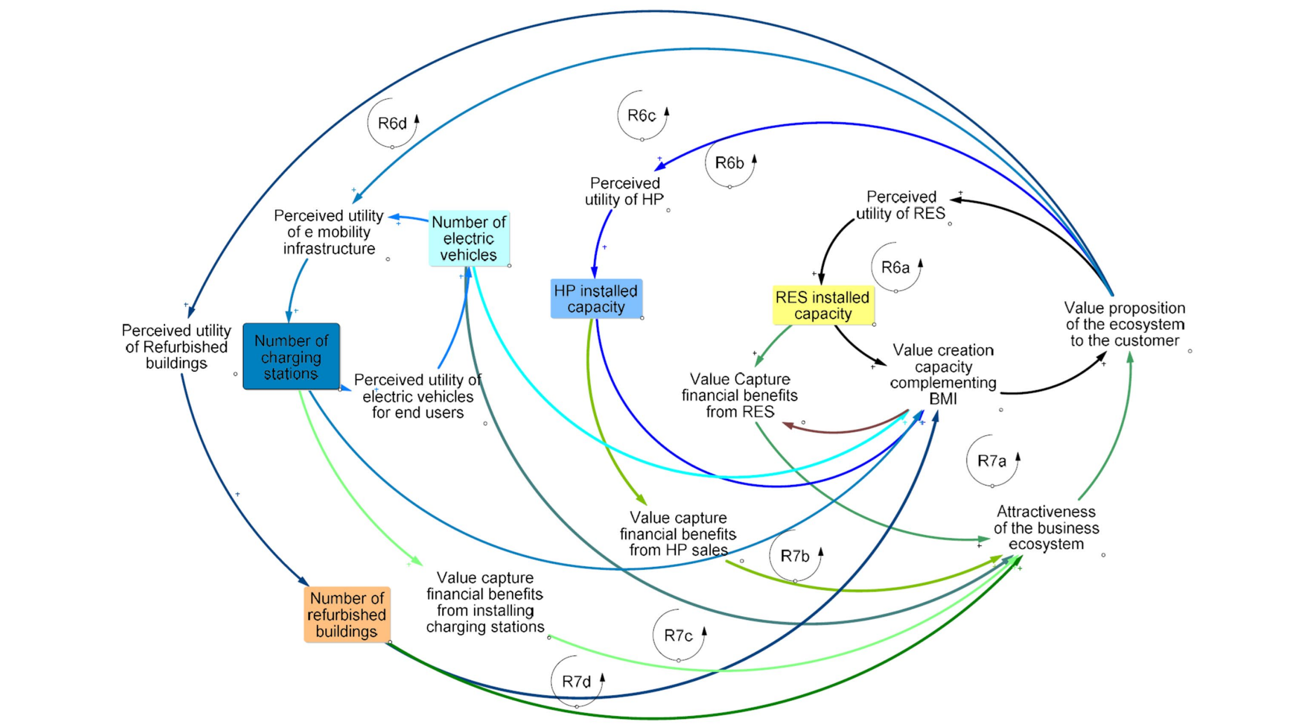

FIGURE 7
Perceived utility of value network.

enhances the value creation capacity of the whole ecosystem. This, in turn, leads to an improved value proposition, for example, through the development of new complementary business models, such as using heat pumps and electric vehicles to increase self-consumption of renewables. Consequently, the perceived utility of these complementary technologies augments. This self-reinforcing effect is illustrated in the loops (R6a,b,c,d).

On the other hand, it has a positive influence on value capture. For instance, increasing the photovoltaic capacity directly leads to larger income for the PV installers. This reinforces the willingness of the keystone companies to participate in the ecosystem. The effect is depicted in the loops "Willingness to participate in the ecosystem" (R7a,b,c,d).

4.3.3 Removing regulatory barriers

In section 4.3.2, we describe how the perceived utility of the ecosystem for the keystone companies, is dominated by a series of reinforcing feedback loops, represented in Figure 8 as R6x and R7x. According to the interview results, these reinforcing feedback loops are weakened by unsupportive regulations.

The balancing loop "Regulatory shortfall" (B6) illustrates how the need of regulatory improvements hinders the value capture capacity of the keystone companies.

In order to compensate this effect, companies can perform lobbying activities. We understand lobbying as delivering key information, with the aim to update decision makers on the current needs of the industry (Park, 2022). The effect of lobbying is represented in the feedback loop (R8).

4.3.4 Perceived utility of residents

Figure 9 shows the perspective of the residents. First, social identification and community sense can influence the attractiveness of a PED project (Bielig et al., 2022). The reinforcing loop R9 illustrates this effect. Furthermore, as illustrated in the reinforcing loop "Increase energy efficiency through behavior change"(R10) the knowledge exchange increases the awareness and engagement of the community participants which can lead to behavioral changes that increase energy efficiency (Burchell et al., 2016; Bielig et al., 2022). Furthermore, we adopted the concept of HEW (Housing, Energy and Well-being) Performance (Eker et al., 2018) to capture the capacity of PEDs to meet several demands of the residents, such as energy affordability and comfort. A better HEW results in a larger willingness to live in a PED community. As the number of residents in a PED increases, the resource pool automatically increases, for example, by enhancing financial capacity or expertise. This helps to improve and expand the value proposition, for example, by improving the comfort of residents. This, in turn, strengthens the HEW performance of the PED. This reinforcing effect is depicted in the feedback loop R11.

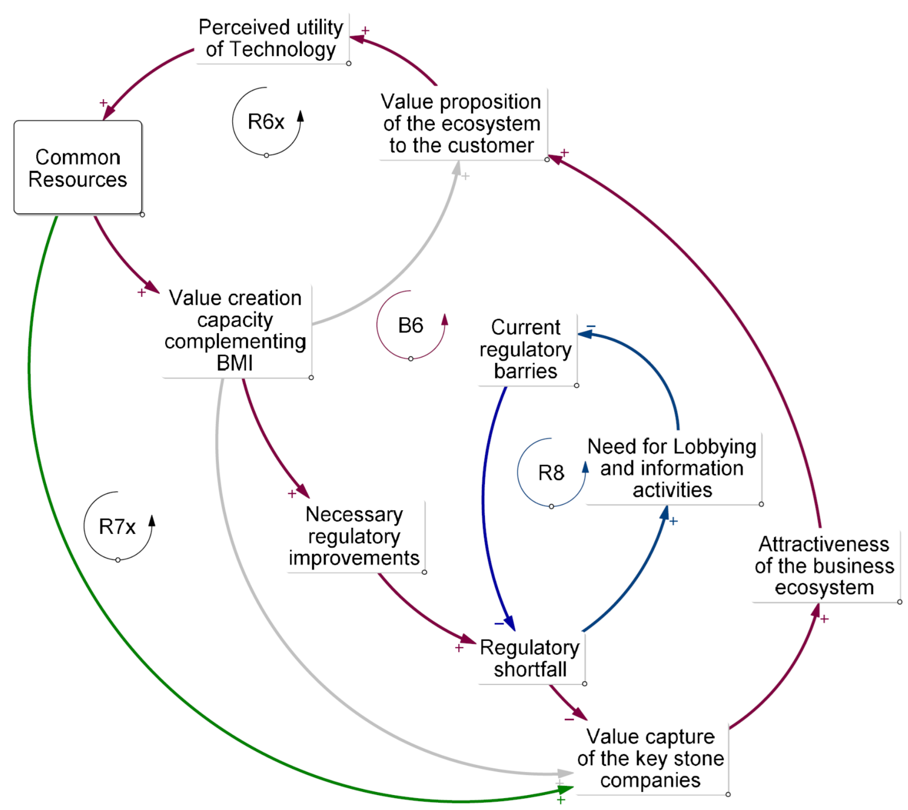

FIGURE 8
Removing regulatory barriers.

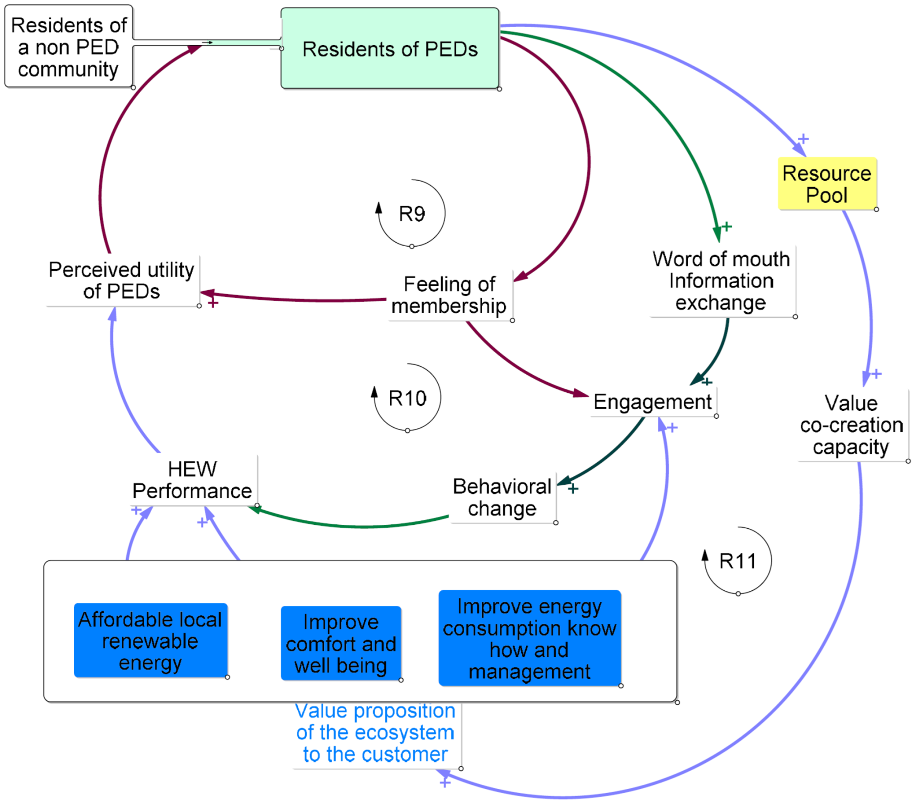

FIGURE 9
Perceived utility of residents.

5 Discussion

This study attempts to identify the dynamic factors affecting the development of PEDs. Using the CEBEP framework, we have mapped the interactions between the different ecosystem actors, identified the common resources and highlighted the political, economic, social, environmental, technical and legal frameworks that affect the development of PEDs. This facilitated the identification of feedback loops.

The causal loop diagrams described in section 4.3 outline a system that is in constant change due to endogenous and exogenous dynamics. Endogenously, the ecosystem actors align their activities to reach common goals, which include decreasing CO_2, increasing the capacity of renewable energy, and improving the housing and well-being of inhabitants. Exogenous dynamics has been identified using the PESTLE analysis and include among other the development of the electricity and fuel prices, the technological development etc.

Two main processes were identified: First, sharing knowledge inside and outside the ecosystem speeds up the development of innovative technologies. Second, the interaction of the actors enlarges the resource pool over time, for instance, by expanding the installed base of renewable technologies, storage, smart meters, and other solutions. As a consequence, potential complementarities among technologies and services emerge, providing new business possibilities and increasing the attractiveness of the ecosystems for the key actors. Agarwal and Kapoor (2023) recognized that complementarities among ecosystem actors are key to align their interests, investments, and strategies. Nevertheless, Adner and Kapoor (2010) and Agarwal and Kapoor (2023) highlight that the success of an innovation largely depends on the innovation of complementarities. These so-called innovation challenges are reflected in the PED case, for instance in the diffusion of electric vehicles and charging stations as mentioned in 4.3.1. Failing to align the innovation efforts results in bottlenecks to value creation.

Furthermore, according to our interviewees, the development of large, ambitioned projects, especially those involving existing districts, entail large implementation delays. This is due to for instance lack of knowledge on the technology installation and use. This is also mentioned by Johansson and Davidsson (2023) who state that the lack of technical expertise hampers energy renovation process at district level.

Additionally, we have highlighted deterring regulations as one of the largest barriers to the diffusion and scalability of PEDs impeding the value capture in a commercial set up. For instance, the regulation for self-consumption associations in Switzerland, also known as ZEV,[2] encourages the exchange of renewable energy among different parties, to increase the self-consumption share. However, the exchange should not be done using the public distribution lines (EnergieSchweiz, 2023). This limits the

2 ZEV is an acronym coming from the German: "Zusammenschluss zum Eigenverbrauch".

establishment of energy communities to building blocks. Consequently, the expansion of PED concepts in larger existing settlements is strongly constrained.[3]

A previous study by Krangsås et al. (2021) also highlights "Governance" aspects, including policy and regulations, as one of the largest challenges for PED development. Nevertheless, regulations as mentioned can be adapted by informing politicians. However, this will require time and may slow down the development.

At the same time, favorable policies and regulations play a crucial role in promoting the widespread adoption of renewable energy sources, smart meters and other PED related aspects. For example, Johansson and Davidsson (2023) mention that financial incentives from governments largely influence investors to perform building renovations at district level.

When questioned about orchestration and the inherent transaction cost associated with it, the respondents did not view this as a significant issue. In contrast, Johansson and Davidsson (2023) often mentioned the lack of coordination among different actors as one factor that hampers the energy renovation process. The difference between these results can be explained on our interview sample: our interview partners represent PEDs projects that either were developed for research purpose or were established on newly built areas. Thus, they did not face significant organizational challenges, and the governance was done by clear contracts among the different companies. Coordination becomes a more significant issue, particularly when applying the PED concept to existing districts, as highlighted by Johansson and Davidsson (2023).

Regarding the benefits of PEDs, our conceptual model also shows how PEDs can create value for multiple actors. Investors seek large profits that are closely tied to the potential for getting new business opportunities. Inhabitants of PEDs benefit from lower energy cost, enhanced comfort, and increased participation, while municipalities benefit by improving their capacity to achieve their CO_2 emission goals and increasing the use of local renewable energy.

Furthermore, another aspect that was mentioned in the interviews, most PEDs have been carried out mainly in the framework of research and development projects. The learnings of these projects will not only enhance the resource pool of the existing ecosystem but also, as highlighted by Evans et al. (2021), they generate knowledge on how experimentation in this area should be efficiently done and how this knowledge is applied to drive administrative change. This kind of understanding is crucial for the replicability of urban transformation projects (Evans et al., 2021).

6 Conclusion and directions to further research

In this study, we aimed to evaluate the PED concept from a co-evolutionary business ecosystem perspective. First, we applied the CEBEP framework to the PED case study of the Hunziker Areal. Based on this, we developed a high-level conceptualization of PED dynamics. The conceptual model was refined and validated in stakeholder workshops with our project partners, who specialize in social and technical aspects related to PED concepts. Additionally, we performed guided interviews with representatives of selected PEDs places to ensure that the CLD captures the most important aspects of the development and adoption of PEDs based on their experiences. Our work has shown the importance of using a systemic approach to assess the potential for using PEDs to improve housing sustainability while creating value for multiple stakeholders.

One of the limitations of this work was the lack of knowledge on PED concepts in Switzerland. This not only limited our interview sample but also the level of detail of our conceptual model, particularly from the point of view of users. Further work will integrate the inputs from our research partners on the technical and social aspects, providing us with the chance to thoroughly analyze and understand the benefits of the PED for residents.

In addition, since most existing PED projects are in the pilot phase, our respondents shared their experiences with this type of projects. This may overlook the positions and needs of practitioners in the field, who will have to adapt their routines by increasing the complexity of the planning process to scale the PED concepts. Nevertheless, some pioneers in Switzerland, such as the "2000-watt society," have started to establish standards that could facilitate the replicability of the concepts.

Additionally, the developed CLD will be operationalized with the purpose of developing a system dynamics simulation model that serve as a virtual environment where we can experiment with different scenarios and perform a parameter analysis to identify the most critical variables affecting the dynamics.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JZ: Conceptualization, Investigation, Methodology, Project administration, Writing – original draft. PS: Investigation, Visualization, Writing – review & editing. SU-B: Conceptualization, Project administration, Supervision, Writing – review & editing.

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3 This would imply the need to construct private transmission lines, to exchange electricity among the different buildings.

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Conflict of interest

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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2023.1266126/full#supplementary-material

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Glossary

BIPV	Building integrated photovoltaic systems
BMI	Business model Innovation
CEBEP	Co-Evolutionary Business Ecosystem Perspective
CLD	Causal Loop Diagram
CO_2	Carbon dioxide
EU	European Union
HEW	Housing, Energy and Well-being
HP	Heat Pump
KPI	Key performance Indicator
PED	Positive Energy District
PESTLE	Political, Economic, Social, Technological, Legal and Environmental
PEUC	prosumer electricity unit cost
PV	Photovoltaic
RES	Renewable Energy system
SD	System dynamics
ZEV	zusammenschluss zum eigenverbrauch