A System Dynamics Approach towards nearly zero energy districts: Stakeholder Interests and the Diffusion of Decarbonization Technologies

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Abstract

Introduction: The transition to near-zero energy districts is shaped by a complex interplay of stakeholder interests, technological complementarities, and market dynamics. This study sheds light on understanding the diffusion of decarbonization technologies by exploring the factors influencing the adoption of photovoltaics, heat pumps, and district heating.

Approach: We develop a system dynamics model to capture the interactions among stakeholders and assess the influence of their interests, ranging from municipalities' CO_2 reduction goals to investors' profitability concerns to residents' energy cost considerations, on the diffusion of renewable energy. The approach allows for scenario testing to assess the influence of different uncertain variables.

Results: The results show that investors' perceptions of financial benefits have a significant impact on the adoption of decarbonization technologies, which in turn leads to lower CO_2 emissions and lower gross rents for current occupants.

Discussion: The study underscores the critical role of stakeholder interests in shaping the energy transition in a district. Future research will extend the model to test innovative business models and policies.

1 Introduction

District decarbonization represent pivotal components of the European Strategic Plan, which supports the European Green Deal in achieving energy efficiency improvements and reducing carbon dioxide emissions of neighbourhoods and buildings. (European Commission, 2023).

A Zero Emission District is a neighborhood designed to minimize greenhouse gas emissions by prioritizing energy efficiency, the use of renewable energy, and smart energy management, while integrating sustainable mobility solutions and cost-effective planning (Brozovsky et al., 2021; Cardoso et al., 2024). There are several strategies that contribute to the path to near-zero energy districts, one is the concept of Positive Energy Districts (PEDs), which, in addition to decarbonization, aims to actively manage local or regional excess annual renewable energy production (Brozovsky et al., 2021; Gollner, 2018).

Planning and developing the decarbonization of a district is a complex task, not only because of the technical complexity of integrating several systems and infrastructures such as mobility, electricity and heating, but also because of the large number of stakeholders involved in a district (Dourlens-Quaranta et al., 2019; Krangsås et al., 2021).

Several authors recognize the importance of identifying and coordinating stakeholders in the planning and operation of decarbonized districts. Krangsås et al., (2021) emphasize that this coordination is challenging due to the diversity of stakeholders who may have conflicting goals and are expected to share information and resources for the successful decarbonization of the district.

Within this framework, the definition and use of key performance indicators (KPIs) tailored to the objectives and roles of different stakeholders is crucial. KPIs are recognized as important parameters to assess a building's performance and monitor its progress across different areas (Carreno, 2024). Additionally, they can help to ensure that the diverse interests of actors are adequately addressed within a shared decarbonization agenda.

Furthermore, authors advocate the use of an ecosystem perspective (Dourlens-Quaranta et al., 2019; Zapata Riveros et al., 2024) when analyzing decarbonization at a district level; this perspective helps to align interests, facilitating the governance of nearly zero energy districts.

In this paper, governance is understood as the framework, rules, and processes by which societies or organizations make their decisions (IOG, 2024). When it comes to nearly zero energy districts governance, there is common agreement on the challenge and importance of this issue, and on the need to develop tools to enhance collaborative governance, fostering co-creation and innovation, and leading to a Just transition, which we understand as a fair and inclusive transition that helps to reduce energy poverty (A. Hearn, 2023; Krangsås et al., 2021; Mihailova et al., 2022).

The goal of this paper is to contribute to filling this gap by developing a system dynamics simulation that enhances the understanding of the dynamics between different stakeholders in the zero energy districts ecosystem and how this can affect the development of these districts. Our research questions are:

- How do stakeholders' interests – perceived benefits and drawbacks - shape the adoption dynamics of nearly zero energy districts?
- What factors and complementarities influence the speed and direction of renewable energy diffusion in achieving net-zero targets?

This paper is organized as follows: Section 2 summarizes the most relevant literature on district decarbonization and PEDs. Section 3 describes the developed system dynamics model. The results are summarized in Section 4. Lastly, Section 5 gives conclusions and suggestions for further work.

2 Literature Review

The involvement and orchestration of stakeholders in district decarbonization projects such as PEDs has often been recognized as one of the most important actions for the planning and the development of such projects (Fatima et al., 2021; A. Hearn, 2023; Krangsås et al., 2021; Li et al., 2017; Mihailova et al., 2022). However, the actual participation of stakeholders in local energy projects may depend on several factors, including their perceived benefits (Delicado et al., 2016).

Recent studies identify key stakeholders in district decarbonization projects, including municipalities, real estate companies, residents, building professionals, technology providers, utility companies and researchers (Larsson, 2022; Li et al., 2017). These stakeholders share not only information and resources but also the benefits from decarbonization projects (Kozlowska et al., 2024).

Understanding the benefits of district decarbonization for key stakeholders is therefore crucial, for example, in devising appropriate incentives for participation (Krangsås et al., 2021). Benefits and impacts are typically assessed using KPIS. These are defined as quantifiable measures of performance that can be used to assess the progress of a project (Walnum et al., 2017).

In the context of PEDs, numerous research projects have attempted to identify the most relevant KPIs (Angelakoglou et al., 2020; Li et al., 2017; Rönty et al., 2020; University of Deusto et al., 2020). The resulting comprehensive lists of KPIs cover a range of dimensions, including environmental, social, economic, mobility, information and technology performance, and governance.

In addition, the KPIs concern a large number of stakeholders at different levels (e.g. national, regional and building level) (Angelakoglou et al., 2020), which measure the benefits of district decarbonization using different KPIs (Zapata Riveros et al., 2024).

Table 1 shows some examples of KPIs for district decarbonization, which have a different level of relevance for some stakeholders than for others. For example, municipalities are often committed to increasing local renewable energy production and thus reducing CO2 emissions; utilities are interested in reducing peak demand; investors, which may be public or private, are interested in the profitability of the project, while residents are more concerned with the cost of energy.

KPI	Unit	RELEVANT STAKEHOLDERS
Increase in local renewable energy production	MW	Municipality and National Government
Peak load reduction	%	Utility company
Carbon dioxide emission reduction	$kgCO_{2eq}$	Municipality and National Government
Return on Investment (ROI)	%	Investor (e.g., Real estate company and/or municipality)
Energy Consumption Reduction Cost	€/kWh	Residents

Table 1 Example of KPIs for zero energy districts (Angelakoglou et al., 2020).

In summary, the path to zero energy districts is complex due to the interplay of different technologies, stakeholders, and their interests and timing. To understand the dynamic complexity to reach net zero goals in time, we use system dynamics (Sterman, 2000). This methodology is well suited to analyze the behavior of complex systems over time. System Dynamics enables the modeling of complex interactions among stakeholders in nearly zero energy districts —including investors, residents, utilities, and municipalities—and analyze how this affects the deployment of decarbonization technologies such as photovoltaics (PV), heat pumps (HP), and district heating (DH).

Previous studies have used system dynamics to analyze the diffusion of PV and HP separately, as well as their co-adoption (Castaneda et al., 2017; Kubli & Ulli-Beer, 2016; Laws et al., 2017; Palucci et al., 2024; Siemer, 2024). However, to the authors' knowledge, the different interests of the stakeholders involved and their influence on the diffusion dynamics have not been consider.

3 Methodology

3.1 Method

We used system dynamics to explore district decarbonization from an ecosystem perspective. Our methodology is depicted in Figure 1. First, we mapped the stakeholders and identified the relevant KPIs. We use system dynamics to assess how different stakeholder perspectives influence district decarbonization.

Afterwards we identify the various feedback loops that influenced the adoption of decarbonization technologies in zero energy districts. This was done through participatory modelling, which resulted in several causal loop diagrams that are described in detail in (Zapata Riveros et al., 2024).

From the causal loop diagrams, we learned that: 1) The diffusion of renewable heating and electricity technology in a district will depend on the perceived benefits to different stakeholders. 2) Complementarities between different technologies will accelerate adoption and 3) Residents are affected by changes in gross rent (increase or decrease) as well as other factors that affect their quality of life.

To operationalize the CLDs, we identify the most relevant technologies and stakeholders that we would consider in our first generic model. Thus, we will focus on studying the diffusion of PV, HP and DH in PEDs, which, according to Zuberi et al., (2021), are economically viable technologies for decarbonizing urban areas in Switzerland. Other technologies such as electric storage, electric vehicles and smart energy management were not considered in this first version of the simulation due to simplification issues.

In terms of stakeholders, we focus on private investors, which finance the project and own the assets, municipalities committed to decarbonization, and residents.

Finally, we perform scenario analysis to explore the behavior of the system and identify the barriers and drivers for district decarbonization.

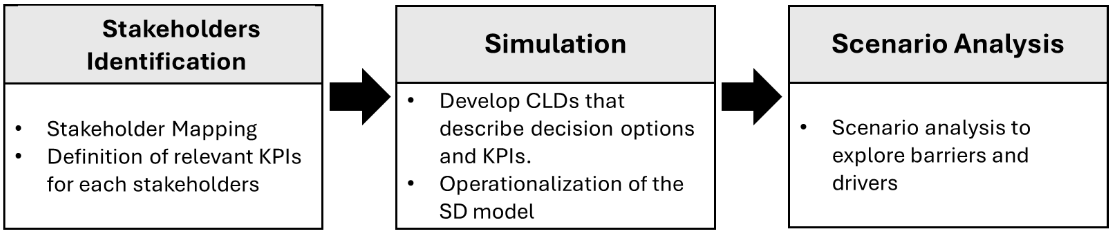

Figure 1 Research Method

3.2 Model Description

3.2.1 Investment decisions

As illustrated in Figure 2, the primary decisions that an investor must consider when evaluating the decarbonization of a building area are primarily concerned with the selection of the most appropriate decarbonization technology.

In Figure 2, the "stocks" measure the number of buildings adopting different decarbonization technologies. Investors can decide whether to install HP PV or DH technologies, or a combination of these. This model captures the decision pathways using flow terms. For instance, the flow "To DH" corresponds to the decision to connect a building to the DH network.

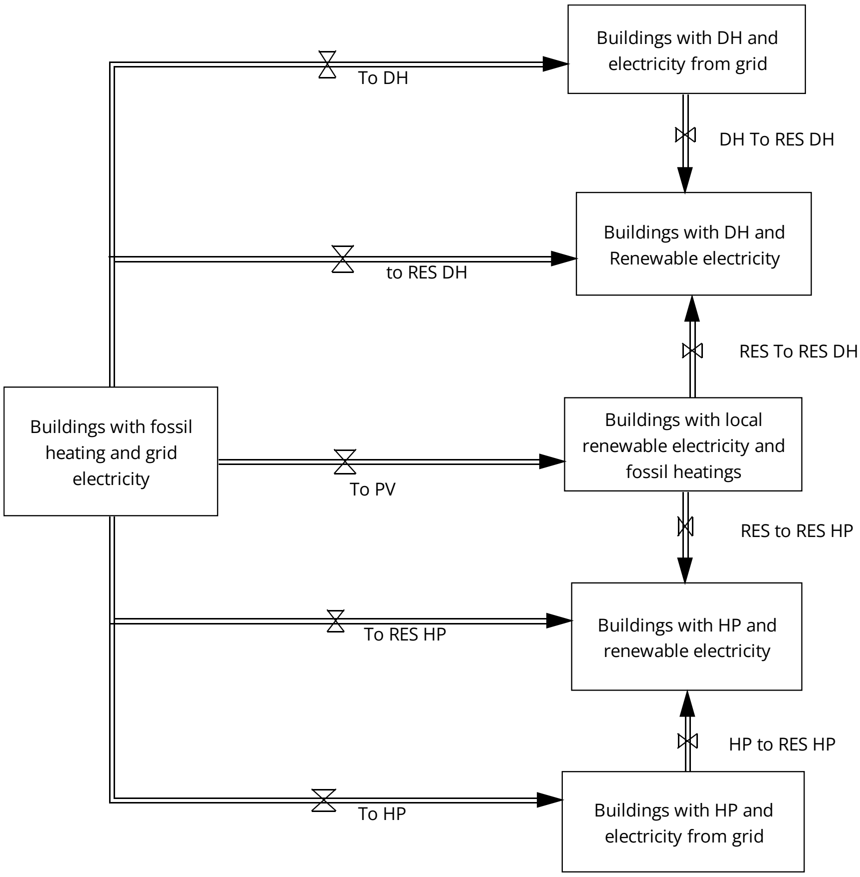

Figure 2 Investor decisions on decarbonization technologies.

The decarbonization path that investors choose is based on the perceived utility of each option. Thus, the adoption rate of each technology (f_i) is estimated by comparing the utility of each option using a logit function as shown in equation (1)

$$f_i = \frac{1}{1 + exp\left[-\beta\left(u_{i,0} - u_i\right)\right]} \tag{1}$$

where $u_{i,0}$ is the dimensionless perceived utility of the current option and u_i is the perceived utility function corresponding to each decarbonization path and β is an empirical shape parameter.

Several factors influence the perceived utility of the investors, as shown in Figure 3. Some of these factors are: 1) Familiarity with the technologies (Loops R1 and R3), which is mainly acquired through word of mouth and contact with the technology provider or energy utility, 2) Peer effect due to direct exposure to the PV technology in the same geographic area (Loop R2) (Kubli & Ulli-Beer, 2016), 3) Scarcity effects, which limit technology adoption to its local maximum potential (Loop B1) and 4) The perceived financial utility. As a result, the total perceived utility u_i of a decision option is calculated as follows:

$$\boldsymbol{u}_i = \boldsymbol{f}_{\boldsymbol{financial}} \times \boldsymbol{f}_{peer\ effects} \times \boldsymbol{f}_{\boldsymbol{familiarity}} \times \boldsymbol{f}_{\boldsymbol{scarcity}} \tag{2}$$

Peer effect, familiarity and scarcity effects are modelled similar to (Zapata Riveros et al., 2021).

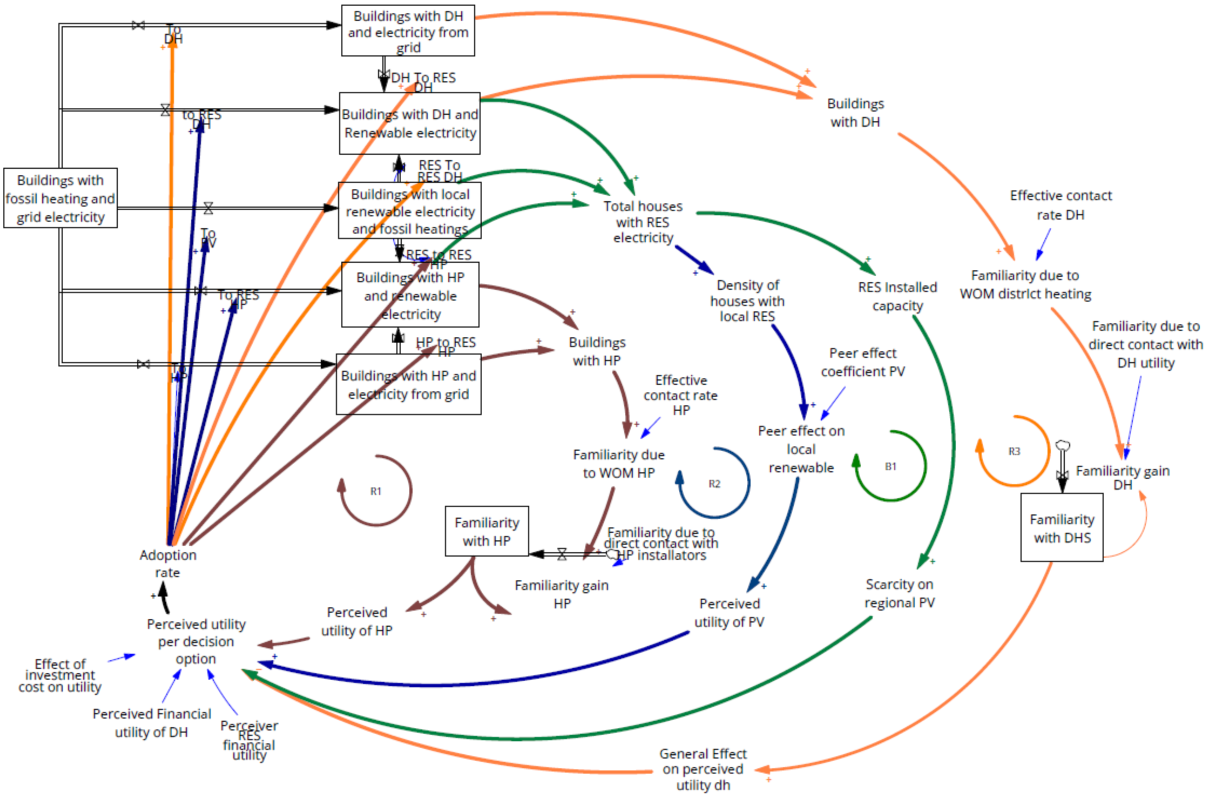

Figure 3 Factors affecting the decision options.

We use the ROI to estimate the perceived financial utility of decarbonization technologies for investors. The ROI is defined as the ratio of a project's net profit to its total investment as shown in equation (3):

$$ROI = \frac{NET\ PROFIT}{COST\ OF\ INVESTMENT} \times 100 \tag{3}$$

As reported by Schläpfer et al., (2020) a private investor considers several factors when assessing the net profit of energy-related investments in his building. A first important consideration is how much of the total investment cost can be passed on to tenants. This aspect is described in detail in subsection 3.2.2.

A second important factor is the increase in the value of the property as a result of energy renovations, including the use of PVs and heat decarbonization technologies. According to (Schläpfer et al., 2022), in Switzerland, the market value of a property with renewable heating can increase by about 3.3 percent compared to a property heated with fossil fuels. Furthermore, Schläpfer & Schmid, (2024) show that this increase can be even higher if HP and PV are installed together in the building.

To the authors' knowledge, there is no study that examines the increase in the market value of a building due to its connection to a DH network. This may be due to the fact that the assumed increase in market value is related to compliance with current and future decarbonization regulations of the building, and most DH systems in Switzerland are not 100% carbon free (Kaufmann, 2024).

However, some utilities argue that when a building is connected to the DH network automatically complies with the current regulation, which requires 10% of renewable energy when replacing a heating system (Increasing this requirement to 20% is currently under discussion (endk, 2024)). We will use scenario analysis to test the effect of the low market value increase of the property in the DH adoption.

A third factor, which mainly affects PV, is the new regulations that facilitate the creation of prosumer communities in a district, allowing reduced tariffs when using the electricity grid, thus improving the profitability of this technology by increasing the self-consumption of local PV (EnergieSchweiz, 2023).

In summary, net income can be estimated as follows (see Equation (4)):

$$NET\ PROFIT = Rent\ increase + Property\ value\ increase + Pv\ income \tag{4}$$

The function used to estimate the financial utility of each path as a measure of the ROI ($f_{financial}$) is presented in Figure 4.

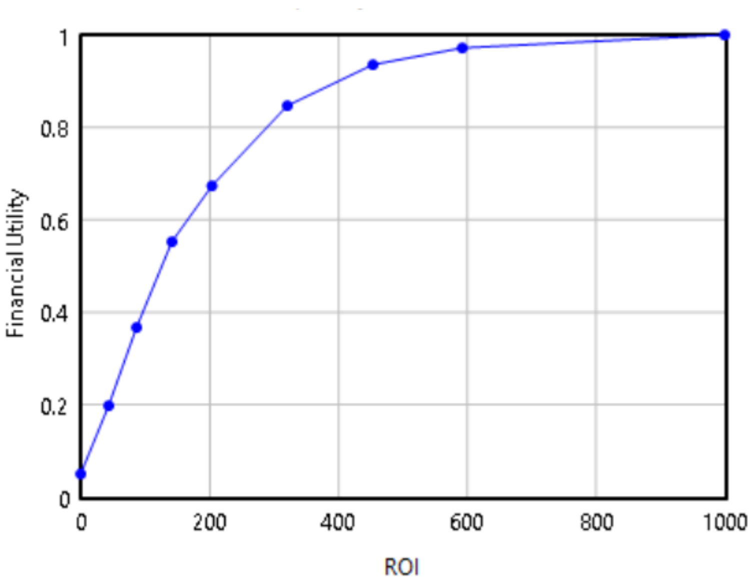

Figure 4 Financial utility as a function of the ROI.

3.2.2 Residents interest- Change in gross rent

In Switzerland, energy-related investments are generally considered to be value-enhancing improvements and consequently, part of the investment costs can be passed on to tenants in the rent (Schläpfer et al., 2022).

The exact amount that can be passed on to the tenant is regulated by law, but the estimation can be complicated, as it depends largely on the type of measures implemented (e.g. replacement of the heating system, windows, PV installation, etc.), and thus it can be assumed that a share of 50 to 70 percent of the investment costs can be passed on (Schläpfer et al., 2022).

The law also specifies how the transferred costs can increase the net monthly rent. However, this only applies to current tenants; for new tenants, the landlord is completely free to set the new rent under a new contract.

Finally, it is expected that the monthly net rent increase will be offset by a reduction in the energy bill, resulting in a lower gross rent.

Figure 5 shows how we have accounted for the change in monthly rents due to energetic renovation in our system dynamics model. We use three main stocks: renovated apartments with current tenants, renovated empty apartments, and renovated apartments with new tenants. This allows us to evaluate two effects: 1) the net rent increase is different for current and new tenants, which is likely to be higher in the latter case, and 2) the effect of vacancy on the ability of investors to recover costs, although vacancy is a rather negligible factor in the case of the major Swiss cities it can become important in the rural areas.

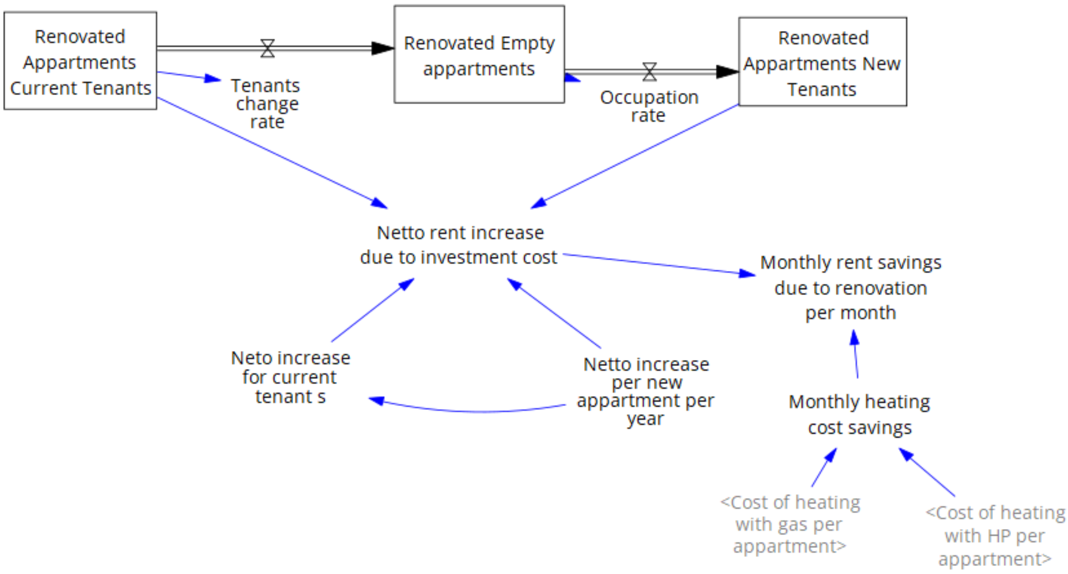

Figure 5 Monthly Rent Change

Finally, monthly rent savings is estimated as monthly energy cost savings minus net rent increase. The monthly energy cost savings are the result of the reduction in heating costs due to a more efficient heating system. Furthermore, in the case that a PV system is installed, due to the difference between the local energy tariff and the price of the external electricity product.

There are several ways to estimate the local electricity tariff, but in any case, the local tariff should not exceed the price of the external electricity product (EnergieSchweiz, 2023), which in Switzerland varies considerably from city to city, being the cheapest price around 0.09 CHF/kWh and the higher 0.45 CHF/kWh (ElCom, 2025).

3.2.3 Municipalities interests- CO_2 Emission Reduction.

We estimate the resulting CO_2 emissions of the district by comparing the emissions of a renewable heating system to a fossil heating system using the equivalents found in Table 2 Similarly, for PV, we compare the emissions of a renewable electricity system with the Swiss electricity grid.

Heating fuel	**CO_2 Equivalent (kg CO2eq per kWh)**
Oil	0.3
Natural Gas	0.2
Electricity mix	0.11
District heating from waste incineration plants	0.03
District heating gas fired	0.106

Table 2 CO2 Equivalent for the studied energy fuels (Source (HSLU & TEP, 2024))

3.3 Data and Scenarios

In order to test our model, we simulate a small theoretical district consisting of 5 buildings with 5 apartments per building. Each apartment has an area of 100m2 which is the average floor space of an apartment in Switzerland (FSO, 2025). Furthermore, we assume that the average heat demand per m2 is 150 kWh/m^{2}a, which corresponds to the specific heat demand of an unrenovated building (Streicher et al., 2019).

Since the utility of district decarbonization is highly dependent on uncertain parameters, we perform scenario analysis to evaluate the impact of some variables. In total, we consider 4 scenarios which are explained in Table 3.

Scenario	Description
Scenario 1: High market value	This scenario is an average scenario where DH is available in the area and the market value of the building increases by 3.3% due to the HP and PV installation.
Scenario 2: Low market value	This scenario assesses the impact of the increase in the market value of the building on the diffusion of decarbonization technologies by setting the percentage increase in the market value of the building due to the HP and PV installation low (0.07%).
Scenario 3: DH Contracting + High Market Value Increase	This scenario evaluates how contracting business models, where the service provider covers upfront costs, influence the adoption of district heating.
Scenario 4: No Market Value Increase for DH	This scenario assumes that there is no increase in the market value of the property when DH is used. This is due to the fact that there is no evidence to support an increase in market value due to DH.

Table 3 Scenario description.

The numerical values that describe each scenario can be found in Table 4.

VARIABLES	UNITS	SCENARIOS				SOURCES
		1	2	3	4	
Property market value increase due HP installation	%	0.011	0.011	0.011	0.011	(Schläpfer et al., 2022)
Property market value increase due to HP and PV installation	%	0.03	0.007	0.03	0.03	(Schläpfer et al., 2022)
Property market value increase due to DH connection	%	0.007	0.007	0.007	0	Own assumption
Percentage of investment that can be passed to the tenants	%	0.5	0.5	0.5	0.5	(Schläpfer & Schmid, 2024)
HP investment cost per kW installed capacity		3000	3000	3000	3000	(HSLU & TEP, 2024)
DH Cost per kW		1500	1500	0.001	1500	(HSLU & TEP, 2024)
ONOFF Contracting		0	0	1	0	
Local electricity tariff	CHF/kWh	0.18	0.18	0.18	0.18	(EnergieSchweiz, 2023)
Feed in Tariff	CHF/kWh	0.03	0.03	0.03	0.03	(VESE, o. J.)
Electricity retail price	CHF/kWh	0.3	0.3	0.3	0.3	(ElCom, 2025)

Table 4 General assumptions and scenarios.

3.4 Model Validation

To verify the structure and key parameters of the model, interviews and workshops were conducted as reported in (Zapata Riveros et al., 2024). However, due to the lack of historical data, a detailed validation of the model was not possible. Nevertheless, we verified the response of the system to extreme conditions and validated the results with our research partners to ensure that the behavior projected by the model is feasible and aligns with their findings, further work will perform sensitivity analysis.

4 Results

4.1 Technology Diffusion

Figure 6 and Figure 7 show the diffusion of the technologies for the analyzed scenarios, we can observe that the adoption of the technology is highly dependent on the assumed increase in the market value of the building.

This is evident when comparing scenarios 1 and 2. In Scenario 1, we assume a large increase in the market value of the building (3.3%) due to the installation of HP and solar PVs, which are complementary technologies. Consequently, the adoption of these technologies is faster in scenario 1 than in scenario 2, which assumes a lower increase in market value (0.07%).

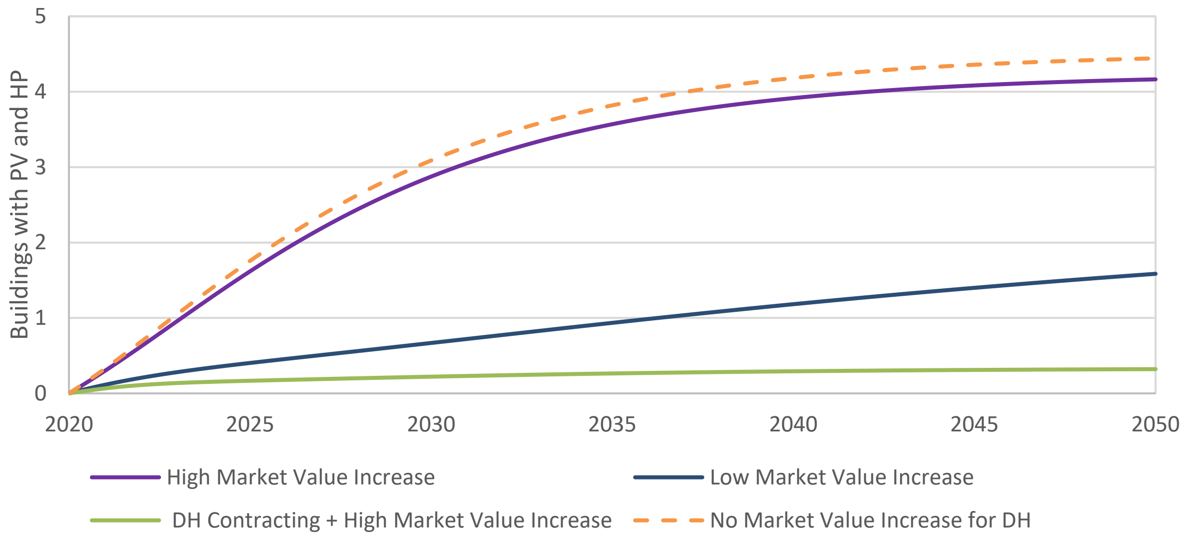

Figure 6 Number of buildings with PV and HP installations.

Scenario 4 examines the assumption that a DH connection does not increase the value of the property. We can see that in this scenario the adoption of DH is very low compared to the other scenarios where the assumed value increase is 0.07%.

Scenario 3 also assumes that a contracting solution is provided. This means that the contractor will pay the upfront cost of the connection, and the investor will pay monthly rates. The results show that this type of business model can accelerate the adoption of DH in the studied district.

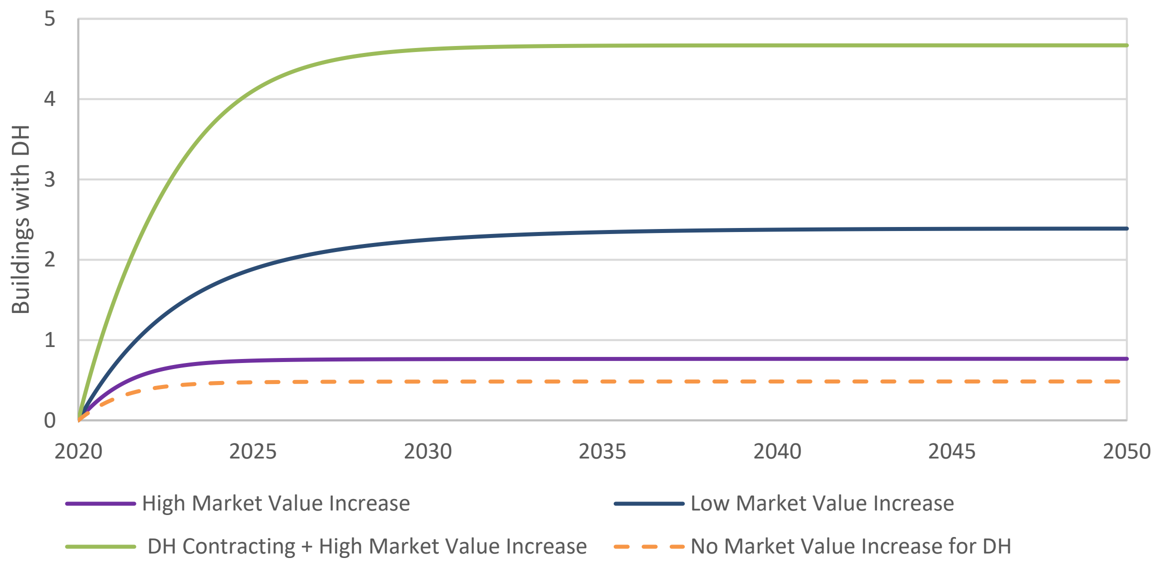

Figure 7 Number of buildings connected to district heating.

Figure 8 shows the installed capacity of PV in the area over time. It is noteworthy that due to the lack of complementarity between DH and PV, the diffusion of PV is slow in scenarios where DH is widespread (e.g., Scenario 3).

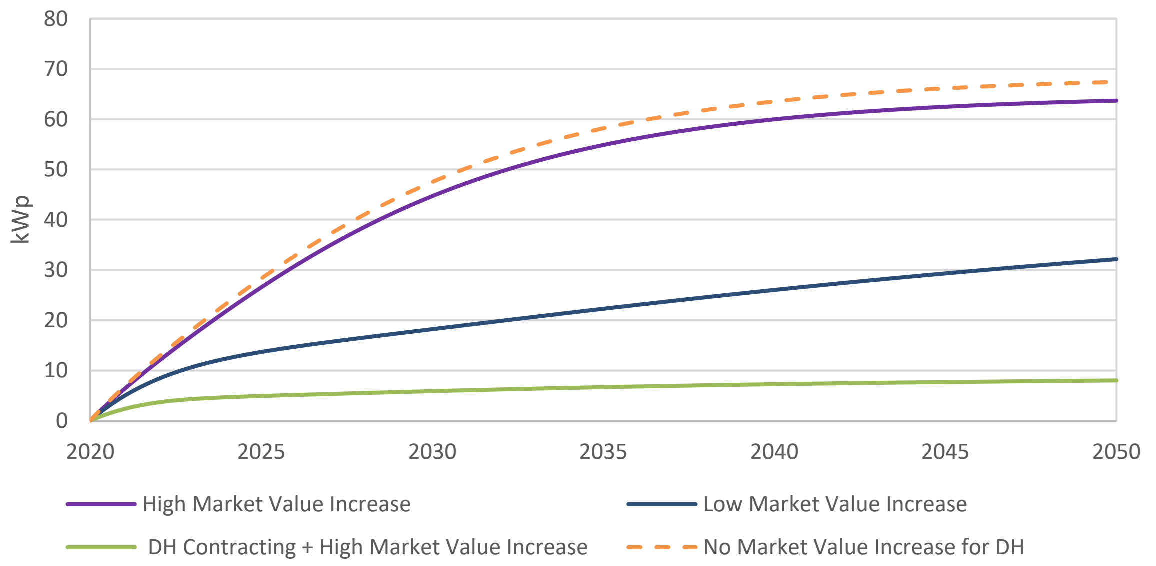

Figure 8 Adoption of Photovoltaics

4.2 CO2 Emissions Reduction

In all simulated scenarios, there is a significant reduction in CO_2 emissions (see Figure 9). This reduction is more notable in the case of district heating, where we assume an emission factor of 0.03 kg CO_2/kWh, which characterizes a DH fueled by waste heat and supplemented with a low share of fossil fuels. However, as shown in (Kaufmann, 2024), the emission factors vary considerably depending on the type of fuel and therefore require further sensitivity analysis.

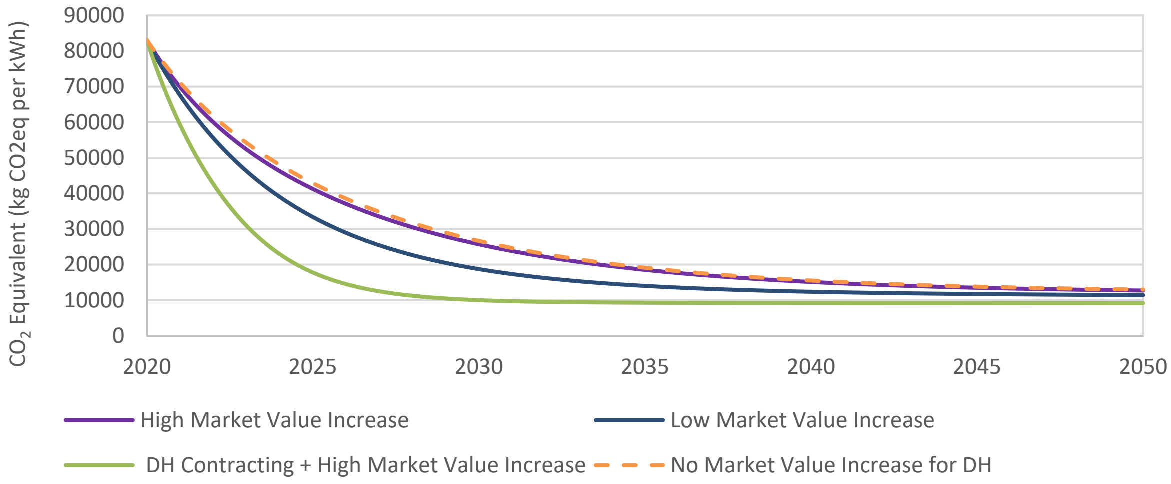

Figure 9 CO2 Emissions of the studied area over the years.

4.3 Return on Investment

Figure 10 represents the ROI for PV and HP, which is used to estimate the perceived financial benefits to investors (see Section 3.2.1). As shown in the figure, the ROI is almost constant over time and is highly dependent on the increase in the market value of the property. In the case of PV and HP, the ROI changes significantly only when a lower market value of the property is assumed; in the other scenarios, the ROI is the same.

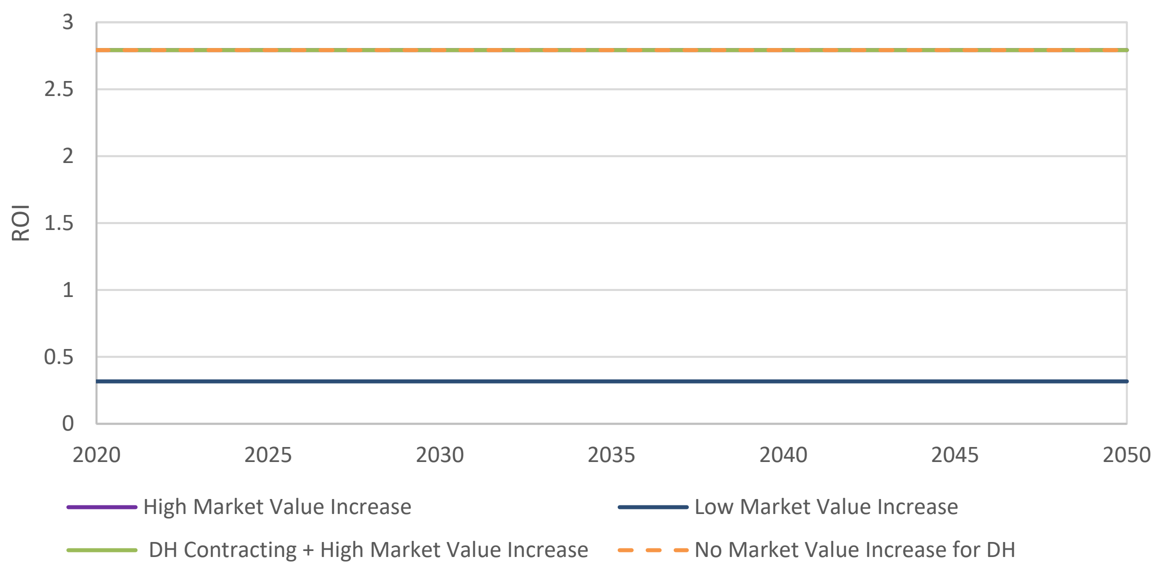

Figure 10 ROI for PV and HP for all scenarios.

Similarly, Figure 11 illustrates the ROI of DH, we can see that if we assume that there is no increase in the market value of the property due to DH, the ROI could even become negative (scenario 4: No market value increase for DH).

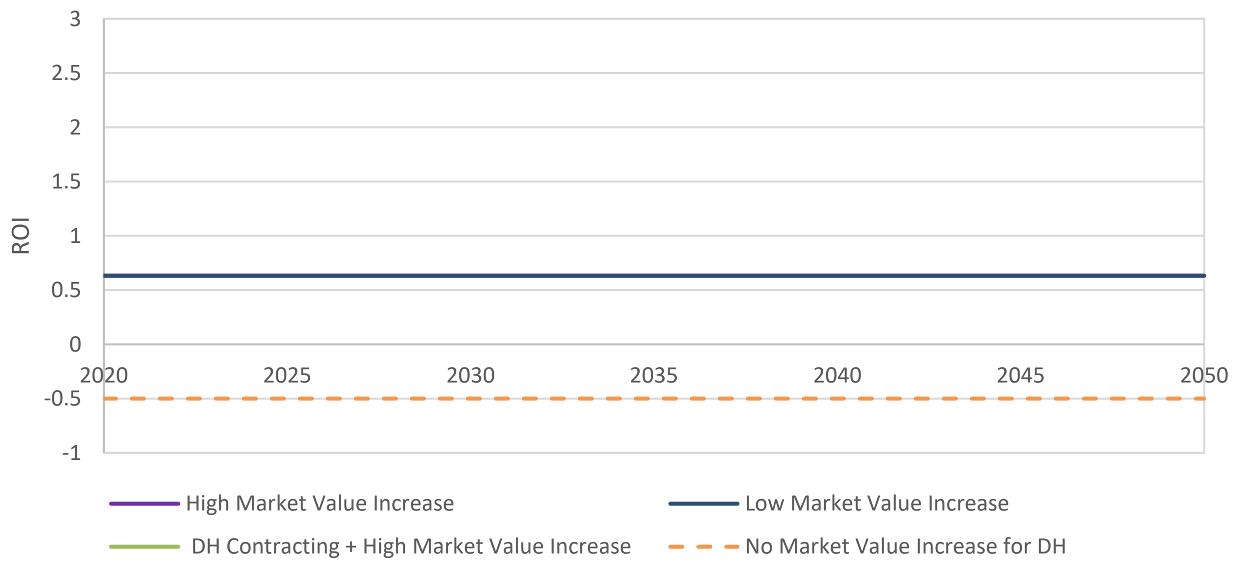

Figure 11 ROI for DH.

4.4 Average monthly rent savings

In all simulated scenarios, the gross rent tends to decrease (see Figure 12). As mentioned in Section 3.2.2, this decrease is due to a reduction in heating costs (see Figure 13), which depends on several factors such as DH tariffs, electricity costs and needs to be subject to sensitivity analysis.

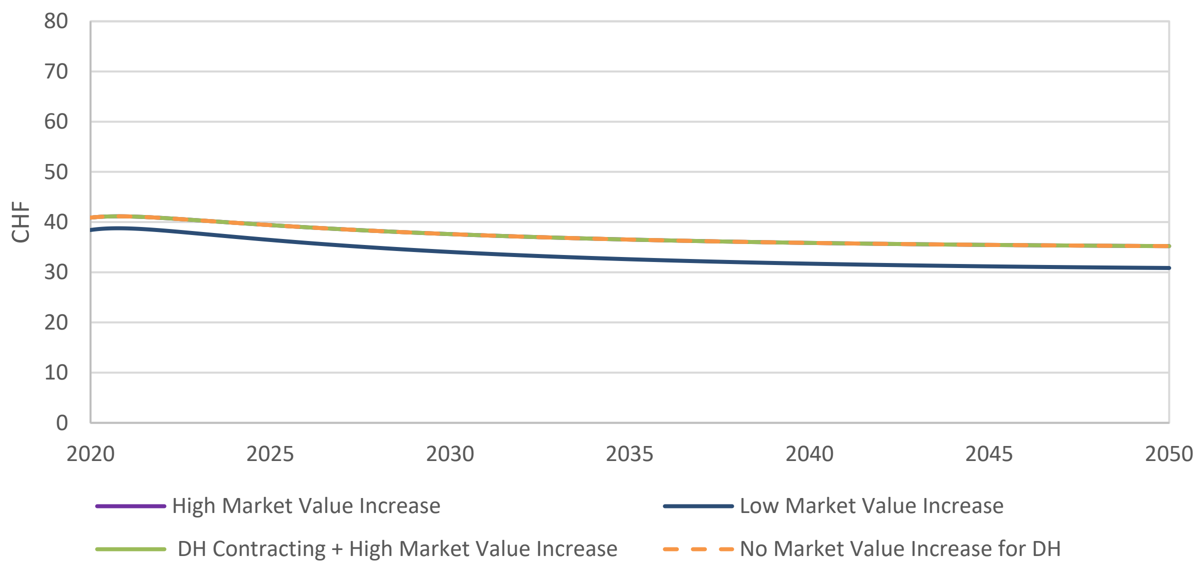

Figure 12 Monthly gross rent savings.

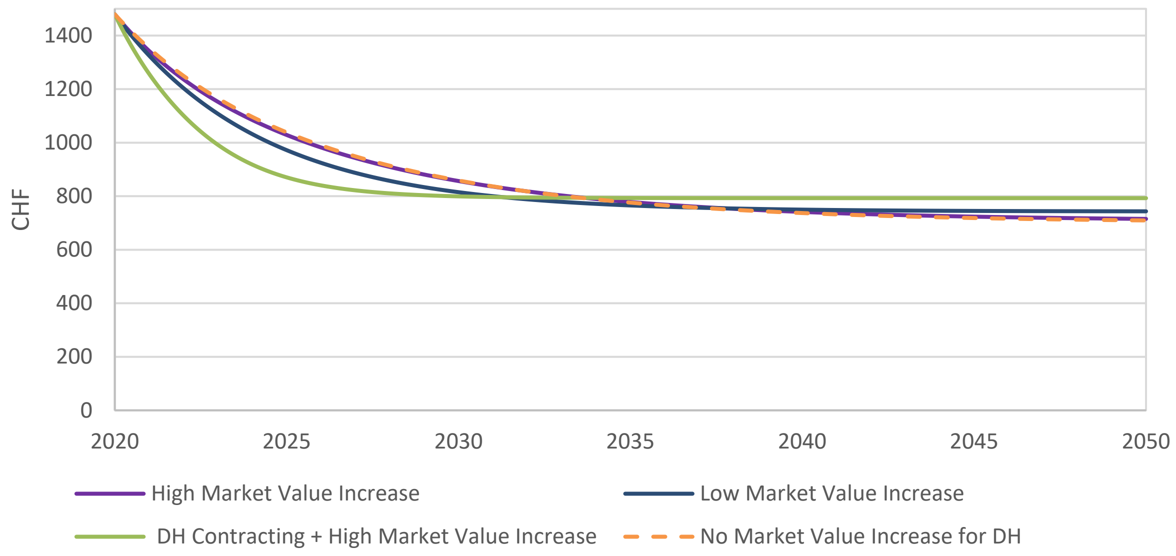

Figure 13 Monthly heating cost per apartment.

Furthermore, it can be observed in Figure 12 that the gross rent savings reduce over time as new tenants move into the building.

5 Conclusions and Further work

This study enhances the understanding of stakeholder dynamics in the development of zero energy districts through a system dynamics simulation. Our findings highlight the significant influence of stakeholder interests, ranging from municipalities' CO_2 reduction goals, investors' profitability concerns to residents' energy cost considerations, on the diffusion of renewable energy technologies.

A key finding of the simulation is the strong dependence of the ROI on the assumed increase in the market value of the property, which according to (Schläpfer & Schmid, 2024) is around 3.3%, in the case of a joint installation of PV and HP, this translates into a very advantageous ROI for the investor and, as a result, accelerates the adoption of these technologies. This result is in line with previous research that emphasizes the importance of promoting the co-adoption of PV and HP to leverage their complementarities (Palucci et al., 2024; Zapata Riveros et al., 2024).

Similarly, the results show that the assumed increase in the market value of the property also has a greater impact on the adoption of district heating. Due to the lack of reliable information, we assume that this increase is rather small (0.07%) or zero which may even turn the ROI negative for district heating since the benefits of DH goes to the tenants and not to the investors, slowing down the adoption of this technology. This is a very critical finding for municipalities responsible for energy planning and district heating planners and operators and therefore requires further expert validation.

Furthermore, results also show that contracting business models effectively accelerate DH adoption but restrain PV deployment due to a lack of complementarities between DH and PV. However, newer generations of DH (e.g. 4^{th} and 5^{th} generations), which deliver heat at lower temperatures, require the installation of a HP at each substation (i.e., each connected building) to raise the temperature (Dang et al., 2024). Therefore, the synergies between HP and PV will become more important.

In terms of CO_2 emissions, all simulated scenarios show a significant reduction in emissions, confirming previous findings that electrification of the heating system, photovoltaics and district heating are crucial for achieving district decarbonization (Costanzo et al., 2024; Zuberi et al., 2021).

In addition, the simulation suggests that gross rent tends to decrease across scenarios due to lower heating costs, benefiting existing residents; this result is critical to informing stakeholders' perceptions of energy poverty, but it should be used with caution since in the long run the homeowner is allowed to increase the net rent to new tenants almost at will, which can cause social difficulties and reinforce the impression that decarbonized positive energy districts are only affordable for the wealthy, as explained by (A. X. Hearn, 2022).

Further research will focus on further testing and extension of the developed model. First, we propose to perform a sensitivity analysis on several variables with high uncertainty and a parameter evaluation to identify the most relevant parameters affecting the results.

Subsequently, the simulation can be extended to test the performance of innovative business models and policies, considering also other types of ownership (e.g. public investors or association).

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7 Acronyms

DH	District Heating
GHG	Greenhouse gas
HP	Heat Pump
KPI	Key Performance Indicator
PED	Positive Energy District
PV	Photovoltaic
ROI	Return on Investment

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