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sweet swiss energy research for the energy transition

Abstract

District heating is seen by many cities as a cornerstone of decarbonized heating supply. The short timeframe of net-zero goals requires a strategic planning approach. However, the time aspect of implementation is often underemphasized in strategic energy planning, so that tensions between public, business and private interests may remain unaddressed in such plans.

We present a System Dynamics model connecting the investment plan with the utility's finances and decision-making by building owners on heating system choice and building energy retrofit. In a synthetic case study representative of Swiss framework conditions, we describe four temporal patterns: 1) delayed revenue growth during ramp-up leads to a financing shortfall and increasing prices; 2) the "utility death spiral" effect is mitigated by cost structure, customer preferences and demand structure; 3) target capacities based on mid-term demand forecasts will be oversized in the longer-term; 4) the impact of technical optimization measures (such as integrating thermal energy storage) is greatest if they are implemented as early as possible. Cities should therefore apply a planning approach explicitly considering the timeline of demand-side decision-making and its interaction with infrastructure development, in line with a socio-political prioritization of costs and benefits for the public, utilities, building owners and tenants.

Abbreviations:

AT	Adjustment time
CHF	Swiss Francs
DH	District heating
DHW	Domestic hot water
GHG	Greenhouse gases
HP	Heat pump
HS	Heating system
kWh	kilowatt hour
MCHF	Millions of Swiss Francs
O&M	Operations and Maintenance
SD	System Dynamics

1 Introduction

To mitigate the effects of climate change, it is essential to reduce greenhouse gas (GHG) emissions as fast as possible. Therefore, many national, sub-national and municipal governments have set targets to reach net-zero GHG emissions within few decades. This entails a reduction of fossil fuel use across all energy end-use sectors. The buildings sector has a key role: for example, in Switzerland, GHG emissions from residential and commercial buildings amount to 22.5% of the country's total emissions, mainly because of the use of fossil fuels for space heating [1]. In cities, this share may be higher: for example, the buildings sector accounts for 54% of direct GHG emissions from the city of Zurich [2]. Therefore, developing low-carbon solutions for space heating is a central aspect of municipal net-zero strategies. Although several options for low-carbon heating at the scale of individual buildings are available, such as air-source and ground-source heat pumps (HPs), district heating (DH) is often an important element of urban energy systems. DH makes it possible to integrate energy sources that would otherwise be difficult to deploy, such as excess heat from waste incineration, industrial processes or data centers, geothermal heat or ambient heat stored in waterbodies [3]. In addition, various factors in urban areas hinder the installation of building-level heat pumps, such as space and noise requirements, protected buildings, and the lack of turnkey systems for large buildings or building complexes [4]. As a result, many cities foresee a substantial development of DH infrastructure in their plans to bring GHG emissions from buildings to zero [5,6].

However, DH systems entail various challenges and uncertainties: as long-lived infrastructure systems, DH grids have high upfront costs and payback periods up to several decades [7]. Various factors may impact the successful rollout and operation of DH over this period [8]. While some of these risks can be mitigated through careful planning [9], the loss of energy sources or anchor customers threaten the security of supply or the economics of a grid [8,10]. Additionally, more gradual developments may threaten the long-term viability of DH systems, such as the increasing competition of decentral HPs [11,12], changing energy prices [13] or decreasing energy demand due to building envelope retrofits and warming temperatures [12,14]. Also, various factors may cause implementation delays, such as interdependencies with other underground infrastructure, construction issues, workforce availability or supply-chain delays [9]. Such delays may be critical, since the viability of new grids or new expansions depends on prospective energy demand, which decreases over time with the uptake of alternative heating systems (e.g. HPs) [15].

There is therefore an interdependency between municipal energy policy and the commercial success of DH systems: reaching public policy goals is contingent upon the development of DH infrastructure, whereas public authorities can take measures to de-risk these investments [16]. In Switzerland, a key instrument is spatial energy planning, delimiting areas where DH is to be developed over the next decades [9]. With the need to accelerate implementation to reach net-zero goals, timing becomes more important: the construction of new infrastructure must be scheduled so that it is technically feasible and financially sustainable. Therefore, internal planning tools such as business plans and implementation schedules become relevant to public policy and are increasingly made public. Nevertheless, the norm for municipal energy plans is still to consider primarily the spatial aspect. Further instruments of municipal authorities are subsidies for building owners to encourage heating system switch, as well as financing infrastructure development to favorable conditions. This study aims to facilitate the consideration of timing in municipal energy planning by using a System Dynamics (SD) model to simulate the implementation of DH infrastructure over time, focusing on decision-making by building owners and the utility's finances. We therefore formulate our two research questions:

> RQ1: How should DH price, market share and financial sustainability be expected to behave over time in the context of massive DH rollouts?
>
> RQ2: How can cities and municipalities ensure that their rollout of DHC is financially and socially sustainable?

In Section 2, we review the state of the research on the implementation dynamics of DH and on the use of SD in local energy transitions. Section 3 presents the methods used to construct the model and introduces the synthetic case study as well as the relevant policies and scenarios. Section 4 presents the model formulation and its application, showing the effect of the selected policies and scenarios. Section 5 discusses the implications of the experiment for research, policymakers and utilities, whereas Section 6 recapitulates the main findings and offers an outlook for further research.

2 Theoretical Background

2.1 The local ecosystem around DH

The current business model of DH has often been characterized as a classical utility model, where the utility delivers energy to building owners without much interaction [17]. However, under transition settings, this view was found to be limited: since DH is often expected to provide public benefits, a purely commercial perspective cannot fully describe the value proposition of DH and how to realize it. Several authors have therefore suggested using an ecosystem perspective on DH [16–18]. A business ecosystem is defined as the set of actors that need to interact if a new value proposition is to be realized [19]. For utilities and municipalities, the challenge is no longer only to define a viable business model for DH, but also to govern the interactions of multiple actors and their sometimes diverging interests.

At the minimum, the local DH ecosystem includes three distinct actor groups: public administration, utility and users. This constellation creates tensions, as users are interested in affordable prices, the utility must recover its costs and the administration typically has a political mission to enable the development of infrastructure for low-carbon heating [9]. An important distinction can be made on the demand side in rented buildings: while the choice of heating system is made by building owners, the costs are borne by occupiers, so that their financial incentives are mis-aligned [20]. Further relevant actors involved in DH development are planners, technology and data providers and building professionals [16,18]. The ecosystem's structure evolves in response to new emission targets, regulatory change, market conditions, changing customer needs or business model innovation [16,17,21]. Furthermore, some modifications of the technical DH system require a deliberate orchestration of actors (typically by the municipality or utility), such as the transition to a smart energy system [22] or the reduction of grid temperature [23]. To summarize, future DH development governance must reconcile diverging interests and coordinate between actors that have so far had little interaction.

2.2 System Dynamics and local energy transitions

System Dynamics (SD) is a methodology focused on operationalizing the causal linkages in complex systems, developing quantitative simulation models in support of decision-making [24]. SD models simulate the evolution of variables of interest over time and are typically used to assess the impact of policy interventions. Among the strengths of SD is its focus on feedback loops and delays, which are often neglected by other methodologies. SD has been applied to a wide range of fields, including to support policymaking in energy transition contexts [25]. A key strength of SD is the explicit consideration of social factors, such as behavior, acceptance or socio-economic measures [26]. At local level, SD has been used to study different transitions in various energy sectors [27]. Its use has been mostly descriptive, and a review notes the potential to better leverage concrete case studies [27].

Various authors have applied SD to study DH systems, with different conceptualizations. The effect of policy interventions at national level to encourage replacement of fossil fuels with renewable energy in DH systems was assessed by Romagnoli et al. [28]. Applying a similar modeling logic at local level, Pakere et al. [29] compared subsidies and carbon pricing on their potential to accelerate the adoption of low-temperature DH systems. These models took primarily a supply-side focus and describe a situation where DH is already widespread. By contrast, [6] uses qualitative SD to describe the situation where a massive expansion of DH is foreseen to replace individual fossil-fueled heating systems. They uncover complex relationships between grid economics, affordability, customer acceptance and the integration of renewable energy sources. Also through qualitative methods, [15] describe the business implications of net-zero targets on municipal DH. Some dynamics are described in both studies: positive feedback between the number of connecting buildings and economic attractivity; competition with decentral HPs, and the complex role of building energy efficiency improvement. However, other dynamics were found to be relevant in one study only: competition with natural gas grids, and lock-in of carbon-intensive heat generation facilities. These differences highlight the need to adapt the modeling focus to local physical and regulatory conditions.

The impact of SD on decision-making processes has, to our knowledge, not been studied in energy transition contexts. Evidence from other sectors suggests that SD helps decision-makers improve their understanding of the relevant dynamics [30]. Therefore, a descriptive application may also be directly of value in supporting decision-making. Similar insights were obtained with technical energy models, which were found to assist sensemaking between diverse decision-makers [31].

3 Material and Methods

This section describes the process to build the simulation model, the synthetic case study to which it is applied and the simulation experiments carried out.

3.1 Model development

The proposed simulation model is a quantitative implementation of the qualitative model proposed by [15]. The construction of the quantitative model is iterative, leveraging and complementing the authors' knowledge of the system (Figure 1). We build upon knowledge obtained on the Swiss DH ecosystem in prior work through interviews, workshops and document analysis [9,15,16]. To construct the model, we start by implementing simple structures, and expanding the model's scope as these are successfully tested [32]. Following the holistic relativist philosophy of SD, model testing focuses on whether the model's structure is correctly implemented (e.g., no technical errors), in line with the authors' understanding of the system, and whether the behavior simulated by the model can be explained with prior knowledge. Challenges in model testing may point to gaps in the authors' understanding of the system, prompting additional knowledge elicitation (e.g., by reviewing the academic and practitioner literature or consulting experts and industry actors). This research benefited from continuous exchange with technical and legal experts on DH in the multi-disciplinary SWEET-DeCarbCH research project.

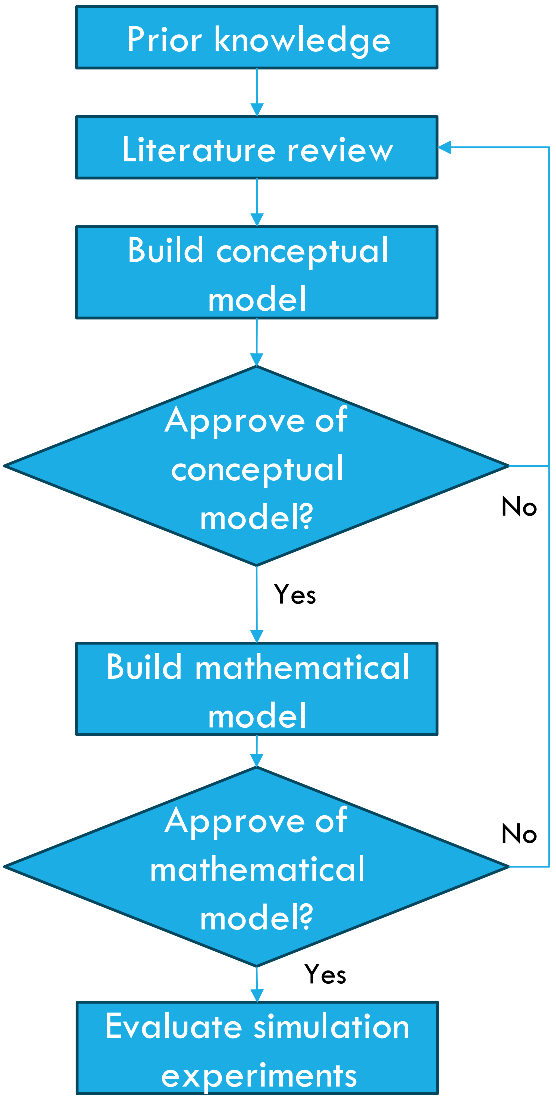

Figure 1: Schematic overview of the model building process (adapted from [32]).

3.2 Synthetic case study

To obtain generic insights, we use a synthetic case study representative of mid-sized to large cities in Switzerland. The variables of interest are: market shares of heating systems, DH price, annualized heating cost and fraction of target DH demand. The focus is on assessing how network effects affect the system's response to delays, environment changes and policy actions. Since the dynamics under consideration are highly dependent upon local characteristics, we use a stylized case to isolate the effects of interest. The case is defined and parameterized using data from several Swiss cities and we emphasize that this does not represent a real city.

The study area is defined as the areas where DH already exists, or future developments are foreseen as per the municipal energy plan. At the beginning of the simulation period, set to 2018, the study area has a total heating demand of 462 GWh/a. An existing DH system supplies 148 GWh/a of heat to buildings within an area historically defined as a DH service area. The primary heat source is the city's waste incineration plant, with auxiliary fossil-fuel boilers acting as a back-up for days of high demand. Within this area, DH has reached a market share of 76%. In the rest of the area, heating demand is mostly covered through natural gas and oil, whereas decentral HPs still have a small market share

(Table 1). To decarbonize heating supply, a revision of the municipal energy plan shows that the locally available renewable energy sources allow an increase of the market share of DH in the whole area from 32% to 80%, accounting for decreasing energy demand by 2050. It is further foreseen to phase-out the natural gas grid in the designated DH area, since two competing grids are expected to be unviable. Therefore, there is a need to develop the heat distribution and generation infrastructure so that an additional 180 GWh/a can be supplied. In the current service area, the target is to maintain the current level of 148 GWh/a. Importantly, a ban on new fossil-fueled HS comes into effect in 2020.

Table 1: List of model parameters and their value in the reference simulation, grouped by subsystem. Values by heating system are given in the order: oil, gas, DH, HP.

Parameter	**Value**	**Units**
Decision-making by building owners		
Initial number of buildings with HS	Area0: 500, 500, 2'000, 50 Other areas (each): 500, 500, 0, 20	Buildings
Initial average heat loss coefficient of buildings	800	W/K
Minimum attainable heat loss coefficient	100	W/K
Annual heating degree-days	3'125	Degree-days
Rate of heat loss coefficient improvement	8	(W/K)/Year
Annual DHW use	42'000	kWh/Year
Consumer prices for oil, gas, electricity	0.1144, 0.1484, 0.2532	CHF/kWh
Investment costs for HS	66'000, 48'000, 62'000, 120'000	CHF
Specific GHG emissions of HS	0.265, 0.202, 0.0972, 0.0023	
Convenience utility of HS	0.5, 0.9, 1, 0.5	Dimensionless
Weight of utility dimensions (financial, upfront cost, environmental, convenience)	0.25, 0.25, 0.25, 0.25	Dimensionless
Beta	3	Dimensionless
Preference for existing HS	0.3	Dimensionless
Initial familiarity with HP in MFH	0.3	Dimensionless
Effective contact rate for HP	0.2	Dimensionless
Finance		
Initial DH price	0.15	CHF/kWh
AT long-term price change	10	Years
AT short-term price change	1	Years
Energy procurement price	0.1	CHF/kWh
O&M cost factor	3%	Dimensionless
Initial infrastructure replacement value	200	MCHF
Initial cash reserve	20	MCHF
Investment and construction plan		
Specific investment cost distribution pipes	1.2	CHF/kWh
Forecasting		
Discount rate	4%	Dimensionless
Time horizon	2075	Year

Amortization period of investments	40	Years

The total costs for the distribution infrastructure amount to 142 MCHF, whereas additional investments of 30 MCHF are required to increase heat generation capacity. A framework credit has been granted by the city to finance these investments. The generation unit is to be constructed in 2020, with a construction duration of three years. The expansion of the DH grid is set to proceed in five overlapping phases, starting in each year from 2025 through 2029. In each phase, construction of the distribution grid is assumed to take three years.

The following simplifications are made: first, the model does not distinguish between buildings of different types or sizes. Rather, the model assumes a standard building, corresponding to a multi-family house with a floor area of 2'000 m^2. The energetic performance of buildings, expressed as heat loss coefficient [W/K], is an average value per area, with a prescribed linear decrease rate to reflect retrofit activity. As another simplification, it is assumed that so-called anchor loads (e.g., large-scale consumers such as hospitals, railway stations, industrial plants etc.) make up one-third of demand in each area and are connected automatically during construction. Finally, meteorological conditions, expressed as annual heating degree-days, are kept constant throughout the simulation.

3.3 Simulation experiments

A range of simulation experiments are conducted to understand the system's behavior and assess its response to interventions or changes in key assumptions (Table 2). The simulations are grouped in four topics: first, a reference simulation reflects the situation described above (S0_Reference). Second, various public policy options are implemented: whereas the reference simulation assumes a ban of fossil-fueled HS, which is current policy in several Swiss cantons, an alternative simulation without such a ban was conducted (S1_noFossilBan). Another simulation considers the obligation for building owners to connect to DH if there is free capacity (S2_mandatory)[1]. Another simulation spreads the expansion phases over a longer period, with a new phase starting every two years instead of every year (S3_spreadInvest). This may reflect workforce shortages, coordination with other infrastructure works, or a policy measure to reduce financial loads. Another simulation reflects a forced improvement of building energy efficiency, with the heat loss coefficient decreasing at 2.5%, instead of 1%, of the initial value each year (S4_forcedEnEff). Two more simulations reflect the integration of a centralized thermal energy storage (TES). In the first case, integrating a TES halves the DH system's specific GHG emissions (S5a_TES_env), while in the second case, it also reduces the energy procurement costs by 25% (S5b_TES_envEcon). In both cases, the TES leads to additional investment costs of 50 MCHF. As a realistic timeline for Swiss cities, construction of the TES is set to start in 2030 and last three years. Finally, two simulations explore two factors identified as uncertain during model construction: first, it is assumed that the only criterion for HS choice by building owners are annualized energy costs, i.e., other utility dimensions, preference for the current HS and familiarity (see 4.1) are neglected (S6_finOnly). Finally, another simulation assumes a greater familiarity with HP in MFH (see 4.1), with the initial value set to 0.6 instead of 0.2 (S7_HP-familiar).

Table 2: Overview of simulation experiments

Experiment name	**Run names**	**Description**
Reference simulation	S0_Reference	Simulation for the synthetic case study with parameter values shown in Table 1.
Public policy options	S1_noFossilBan	No ban on fossil-fueled HS.
	S2_mandatory	Connection to DH grid is mandatory for new HS if there is available capacity.

[1] While some Swiss cities have a mandatory connection policy, exceptions for renewables-based HS are usually permitted. This is *de facto* identical to a fossil-fuel ban. Rather, S2 is an extreme scenario maximizing the market share of DH regardless of decision-making by building owners.

	S3_spreadInvest	Construction of distribution grid in a new area starts every 2 years instead of every year.
	S4_forcedEnEff	The annual energy efficiency improvement rate of buildings is set to 2.5% of initial heat loss coefficient.
Integration of centralized TES	S5a_TES_env	A centralized TES is integrated, which halves the DH system's specific GHG emissions.
	S5b_TES_envEcon	A centralized TES is integrated, which halves the DH system's specific GHG emissions and enables energy procurement cost savings of 0.025 CHF/kWh.
Key uncertainties	S6_finOnly	The financial utility dimension is weighted at 100%. No preference is given by building owners to the existing heating system.
	S7_HP-familiar	Initial familiarity with HP in MFH set to 0.6.

4 Results

This section gives an overview of the developed model and presents the results of the reference simulation as well as the simulation experiments.

4.1 Model formulation

An overview of the model is given in Figure 2[2]. The model links four subsystems, each described in the following subsections. As can be seen in Figure 2, the model includes several feedback loops. Economies of scale are represented through a positive effect of increasing connections on cash flow (green loop) and forecasted demand (orange loop), both with the effect of decreasing consumer prices and making connections financially more attractive [6,15]. Conversely, this suggests the possibility of a "utility death spiral", where declining demand leads to increasing costs for remaining customers, prompting more disconnections [6,33]. There is also a balancing effect of pricing, mediated by the utility's cash reserve: since a non-profit operation is assumed, price increases and subsequent improvements of the utility's finances limit the need for further increases. On the other hand, if the utility incurs deficit, this leads to additional capital costs in the form of interests, further increasing financing needs. Finally, it was found necessary to include another positive feedback loop to model the diffusion of the key competing technology for DH, HP: the more HP are installed, the more familiar building owners, planners and installers are becoming with this solution [34].

The model is implemented in Vensim DSS 10.3.0. The simulation runs from 2018 to 2070, with a time step of 0.125 years.

[2] A more detailed model documentation, along with the Vensim model file, is available under https://github.com/mspeich/SCOVILLE

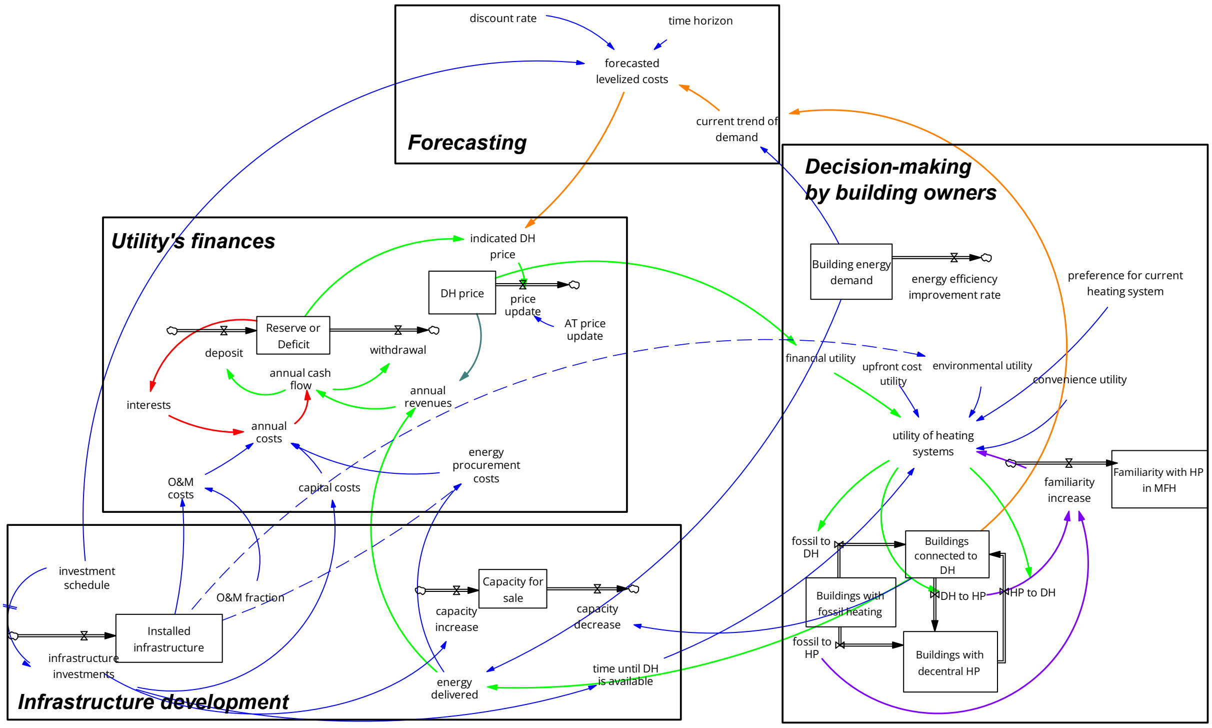

Figure 2: Overview of the subsectors of the SD model and linkages between them.

4.1.1 Decision-making by building owners

Buildings are assigned to one of five stocks, depending on the heating system currently installed. Four stocks represent the heating systems represented in the model (oil, gas, DH and HP), whereas a fifth stock keeps track of the buildings that have committed to connecting to DH but have not physically done so yet. These stocks are replicated for each area. Buildings change stocks following the owners' decision to switch heating systems. Each of these flows are modeled as follows:

$$switch_{HS1,HS2} = \frac{HS1 * share_{H1,HS2}}{AT_{HS1}}, \quad (1)$$

where $switch_{HS1,HS2}$ is the number of buildings switching from heating system HS1 to HS2 (e.g. from oil to DH) per year, $HS1$ the number of buildings equipped with HS1, AT_{HS1} represents the share of buildings with HS1 replacing their heating system, $share_{H1,HS2}$ the share of those buildings that chose option HS2. Typically, AT_{HS1} is the average lifetime of a HS (i.e., 25 years). However, to account for the transition dynamics, the AT's also depend on the average age of HS, tracked following [35]. For technologies to be phased out (fossil-fueled HS), the AT decreases with average age, until all systems are replaced when the average age reaches 35 years. For HP and DH (in new areas), the AT is set to zero in the first ten years to avoid simulating very recent HS being replaced.

HS choice is modeled as a discrete choice, i.e. the share of buildings is calculated using a multinomial function in which the utility of HS is compared to each other:

$$share_{HS1,HS2} = \frac{e^{(\beta * u_{HS2})}}{\sum_{HS1-n} e^{(\beta * u_{HSn})}} \quad (2)$$

The utility of each heating system is a weighted combination of four utility dimensions, further modified by four contextual factors. The four utility dimensions are: 1) financial utility, expressed as the annualized costs of each heating system benchmarked against the cheapest option, 2) upfront cost, where higher investment requirements lead to a lower utility [33], 3) environmental utility, expressed as the specific GHG intensity of each heating system, and 4) a scalar representing the convenience of each heating system as perceived by building owners. For DH, financial utility is determined endogenously, while they are determined exogenously for the other heating systems. The other dimensions are prescribed.

The utility of DH is subject to two more constraints: having to wait for a connection makes this option less attractive, so that the utility of DH is reduced when the grid is not yet built. Also, there is a limited amount of capacity for sale, so that a scarcity-dependent function enforces this limitation [33]. For HP, the model accounts for the fact that HP in MFH are still perceived skeptically by building owners, and many building professionals do not yet have the skills to plan and install large HPs [36]. Therefore, the adoption of HP depends on familiarity with this solution, which increases over time as the market share increases [37,38]. If familiarity is not yet at 100%, the utility of HP is reduced accordingly. The initial familiarity value is set at 0.3, and the effective contact rate at 0.2. Finally, the model accounts for building owners' preference for their existing HS [39]: in equation 2, the utility of every HS except HS_1 is reduced by 30%.

Building energy efficiency improvements are represented through reductions of the average heat loss coefficient at a prescribed rate (see 3.2). Annual heat demand, calculated as the product of heat loss coefficient and annual degree-days plus constant DHW demand, impacts the financial utility term for each HS by determining the operating costs of each HS.

4.1.2 Utility's finances

The finances subsystem calculates the net annual cash flow (sum of annual costs and revenues), updates the financial stocks (cash reserve, investment debt and a possible additional deficit) and calculates the unit price for DH[3]. Annual revenues are the product of energy sales and unit price, whereas annual costs include capital, O&M and energy procurement costs. The case study assumes that the utility finances its investments through pre-defined credits with linear amortization over 40 years and a discount rate of 4%. O&M costs are a fixed fraction (set to 3%) of the installed infrastructure's replacement value, whereas energy procurement prices are kept constant in this simulation.

The unit price is modeled as two stocks: a long-term and a short-term price component (for simplicity, these are shown as a single stock on Figure 2). The stocks are updated to reach an indicated value, with a time parameter accounting for delays in price adjustment [33]. Indeed, since frequent adaptations of tariff formulas are not perceived well by customers [9], there is a social constraint on this frequency. The indicated long-term component consists of the levelized costs until the time horizon (set to 2075), based on outputs from the forecasting subsystem. The short-term component, which may be positive or negative, aims at reaching short-term financial goals: eliminating unplanned deficits if present, keeping the reserve around a target level and ensuring that annual revenues match the costs. The latter goal means that if the short-term price component is updated frequently, DH price is almost completely driven by current costs, whereas a lower update frequency gives more weight to the long-term levelized costs.

4.1.3 Forecasting

The forecasting subsystem returns an estimate of long-term costs and energy sales. Since these estimates are used to calculate levelized costs (see above), both costs and sales are discounted [40]. This is done by integrating the product of the estimated cash flow or sales with an exponential discounting function. While capital and O&M costs are entirely predictable, energy sales and the associated energy procurement costs cannot be known in advance. To estimate these, the model simply extrapolates from current energy sales using a five-year trend. Before the grid is expanded to a new area, future energy sales are estimated using standard assumptions: demand will reach half of the target value during construction of the distribution grid, and the target value will be reached within 12 years.

[3] As a simplification, the price is not disaggregated into a per-kW and a per-kWh component but taken as a composite price in CHF/kWh. Furthermore, the model assumes that service pipes and substations are paid by the building owners, which is reflected in the (prescribed) investment costs.

4.1.4 Implementation plan

In the current model, there is no feedback between the implementation plan and the other subsystems. Therefore, this subsystem simply tracks the construction and investment progress of various infrastructure components (distribution and transmission pipes, generation units and storage), all according to a prescribed schedule. In the future, the implementation plan may be influenced by the utility's financial situation [6,15].

4.2 Reference simulation

In the reference simulation (Figure 3), the market share of fossil-fueled HS starts declining after new such HS are banned in 2020. This is accompanied initially by a steep increase in the market share of HP, until the rollout of DH allows more connections from 2025 on. Then, DH reaches a market share close to its target within a few years. After 2035, there is little change between the market shares of DH and HP. The DH price, starting from an initial value of 0.14 CHF/kWh (set to obtain a balanced cash flow initially), increases as soon as the first investments are made to reach almost 0.2 CHF/kWh by 2030. This reflects the additional capital and O&M costs while revenues could not yet grow. For a typical apartment, this means an increase of about CHF 350, or 18% of their annual heating costs, within a few years. Finally, while market share remains quasi-constant after 2035, the connected demand steadily decreases due to increases in building energy efficiency. As seen in the price curve, however, this does not lead to a utility death spiral.

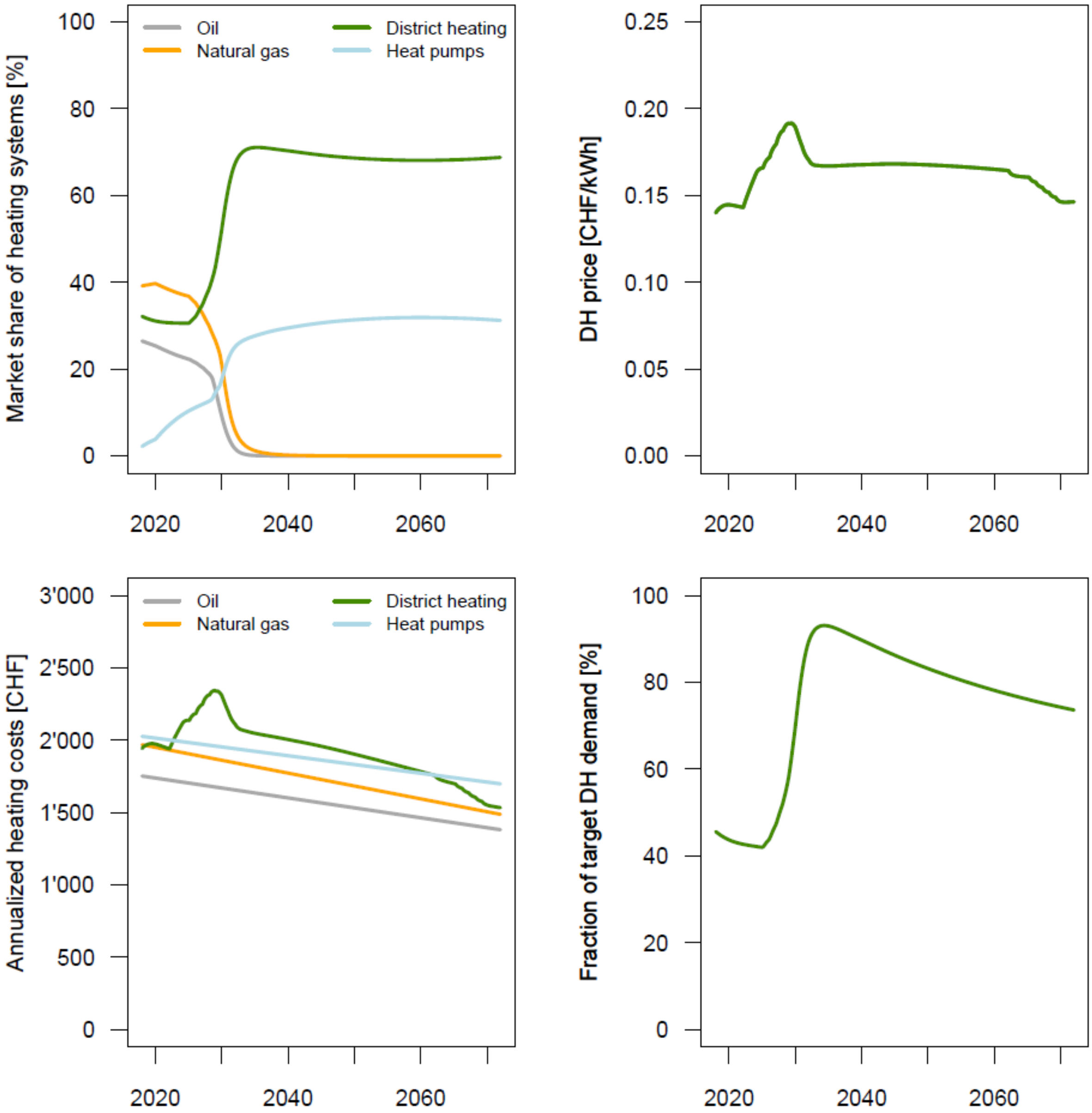

Figure 3: Results of the reference simulation for four variables of interest: market share of heating systems, DH price, annualized heating costs for a typical apartment, and fraction of target DH demand

4.3 Simulation experiments

Different public policy options have a profound impact on the market share of DH (Figure 4). Without a ban on fossil-fueled HS, the market share of DH increases very slowly and never reaches the target value. By contrast, mandatory connections cause the market share to increase faster than in the reference simulation. A spread-out investment schedule causes an initial lag in DH market share, but there is little difference with the reference simulation from 2035 on. Finally, the forced energy efficiency scenario causes a higher market share by 8 percentage points in 2040.

Scenario S1_noFossilBan leads to substantially higher costs for users, both during the peak and throughout most of the simulation. Compared to the reference simulation, S2_mandatory and S3_spreadInvest alleviate the peak somewhat, then remain close to the reference. The lowest costs are obtained with S4_forcedEnEff (it should be noted that the costs of building retrofit are not considered here).

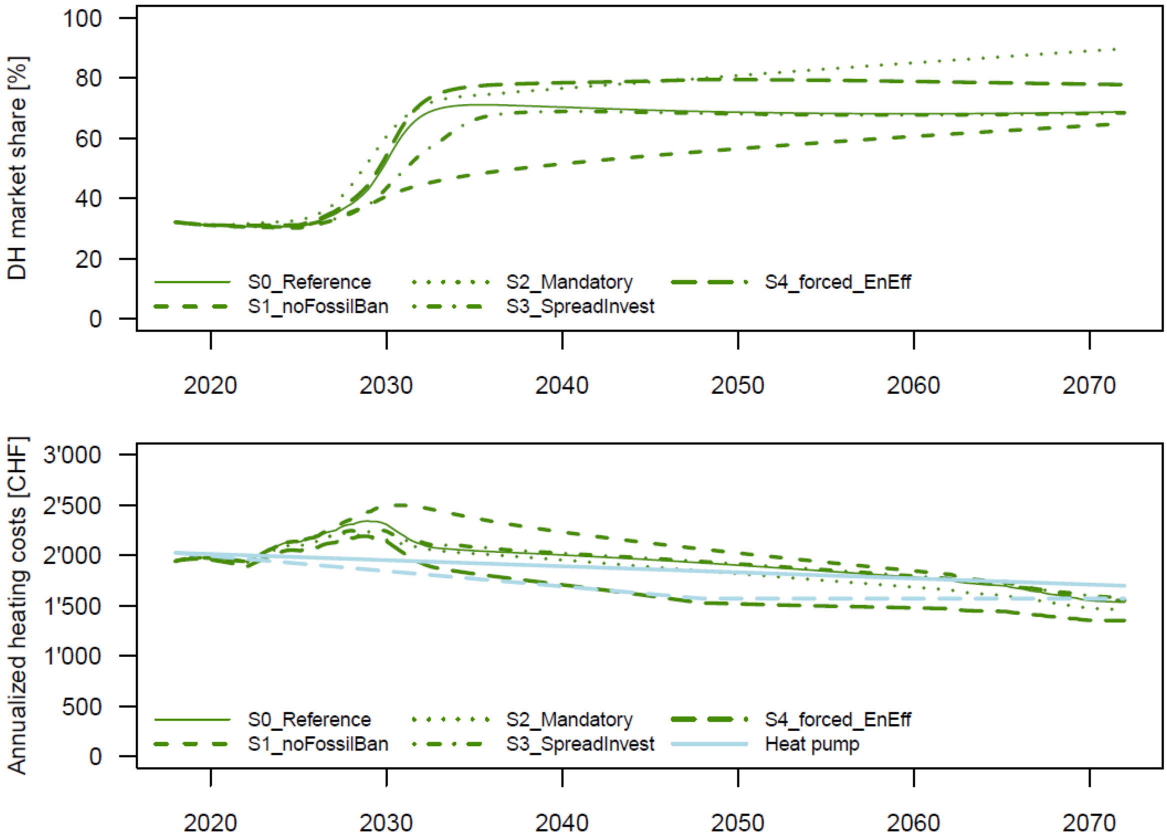

Figure 4: Effect of four public policy options on the market share of DH and on annualized heating costs.

Integrating a centralized TES causes virtually no change to the market share, regardless of whether the TES brings economic benefits in addition to environmental benefits (Figure 5). After commissioning in 2033, costs for users are roughly CHF 150 higher (S5a_TES_env), resp. CHF 100 lower (S5b_TES_envEcon), whereas before commissioning, costs do not decrease as fast as in the reference simulation.

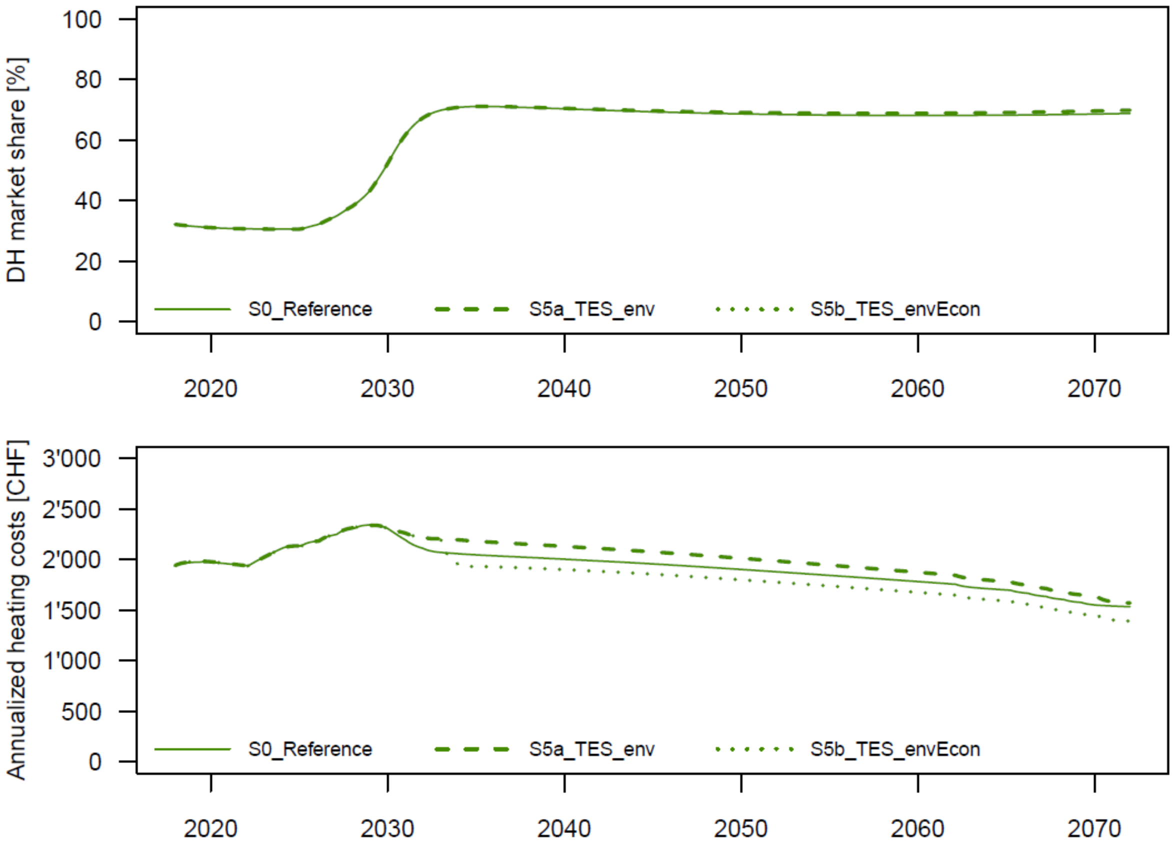

Figure 5: Effect of integrating a centralized TES on the market share of DH and on annualized heating costs.

Basing decision-making by building owners on financial criteria only (S6_finOnly; Figure 6) leads to a market share that never exceeds 50%, versus 70% in the reference case. This is accompanied by very high costs for users throughout the simulation. By contrast, increasing the familiarity with HP (S7_HP-familiar) has no substantial effect on model results.

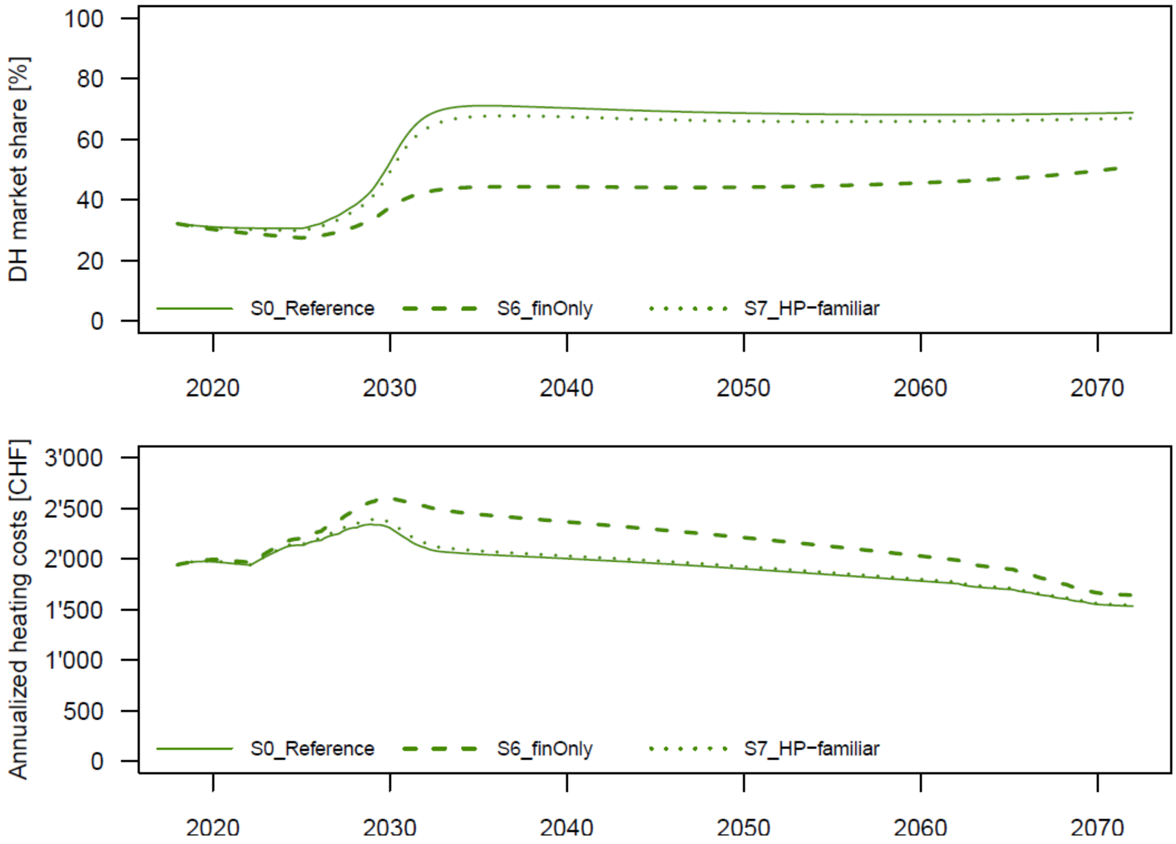

Figure 6: Effect of considering only financial utility in heating system choice (top) and of increasing assumed familiarity with heat pumps in MFH (bottom) on the simulation.

5 Concluding discussion

The model presented here has shown behavior patterns with potentially profound implications for the planning of future DH rollouts. First, a clear financing shortfall is apparent at the beginning of the rollout. At that time, capital and O&M costs greatly increase, while the additional revenues have not yet grown enough. To recover these costs, the model increases the price for users. This is in line with international observations that (re)financing DH investments is challenging [41,42] and is also reflected in current controversies in Switzerland on DH pricing [43]. Price increases by municipal DH utilities may lack acceptance by the public, as people may refer to DH's natural monopoly status [44] or instances of cross-subsidization of other utility services [45]. By contrast, our simulation results show that such a shortfall is inevitable and, in the absence of mitigating measures, will lead to higher consumer prices. Therefore, price increases are not necessarily evidence of abusive pricing policies.

A second observation is that, although a utility death spiral is in theory possible with the assumed causal structure, this does not necessarily happen when demand declines. Perhaps most surprisingly, in a scenario with forced building envelope retrofit, the market share of DH is higher than in the reference case and prices are lower. This may be explained by the lower overall operating costs, i.e., reduced energy demand weakens one of the key strengths of HPs, making DH comparably more attractive. The robustness of DH is also due to the share of demand not concerned by envelope retrofits, i.e., DHW demand and anchor loads. Furthermore, the cost structure in the assumed case offers another explanation: energy procurement costs, i.e. variable costs, represent more than half of total costs. The case study implicitly assumed a conventional, high-temperature system. In line with technical simulation studies [46], this cost structure lowers the sensitivity of DH to decreasing demand. With future DH systems becoming more CAPEX-intensive, this sensitivity may increase. This is reflected in the indicated business model change that should accompany DH modernization, i.e., less reliance on economies of scale [17]. The model also suggests that spreading DH investments over a longer period will allow the utility to reach the same market share as in the reference case with a delay of only few years. This might suggest that doing so is a “safe” strategy to alleviate financing pressures without risking market share losses to HP. However, we note that the decision-making assumptions in the model are highly uncertain, as there is little empirical research on the preferences of building owners when choosing between DH and HP [34]. As shown in the simulation experiments, varying those assumptions can have a dramatic effect on the viability of DH.

A third observation is that the target capacity for the medium-term may lead to oversized systems in the longer term. This study has replicated the common practice in strategic energy planning of defining a target capacity for the time horizon of net-zero goals (e.g., 2040-2050), accounting for expected energy efficiency improvements until then. Nevertheless, as soon as DH market share reaches its maximum (i.e., around 2035), demand starts declining. On one hand, this may be an opportunity in the future: freeing capacity may facilitate the expansion to further areas (within the limits of physical constraints for viable expansion, see e.g. [47]). On the other hand, this points at potential to integrate solutions such as demand-side management already in the planning phase. As such solutions can greatly reduce peak loads [48] and may lead to substantial investment cost reductions [49], this could be a promising strategy to alleviate the financing pressure described above.

Finally, this study has examined the effect of integrating a centralized TES. TES potentially offer various benefits to DH systems and their actors [50,51]. Nevertheless, in the simulations, these benefits do not lead to a difference in DH market share compared to the reference. This may be reflected by the timing of implementation: while many Swiss utilities are currently considering integrating large-scale TES, only few concrete projects have been started. At the same time, DH rollout is well advanced. Therefore, commissioning by 2033 was seen as a realistic timeframe for an average Swiss city. At that time, most building owners have already made their decision for a new heating system. The benefits of TES are not apparent before commissioning, but the costs are already reflected in the price. This example highlights the importance of timing on the concrete value that infrastructure investments bring: whereas the TES in this example has a positive environmental impact and, in one case, a positive impact on costs for users, an earlier implementation may bring even more benefits, e.g., an increased DH market share. Such timing effects should be considered when strategic energy planning incorporates the time dimension more explicitly [52].

5.1 Recommendations for research

This study has highlighted a crucial research gap: little is known on the decision-making of building owners when fossil-fuels are no longer available. Research has so far adopted a “low-carbon versus fossil” focus, with HP and DH often lumped together [39]. As measures such as the fossil-fuel ban explored here become more common, it is essential for the planning of DH rollouts to know which factors influence building owners’ decision under these new circumstances.

5.2 Recommendations for policymaking

This study has shown the value of adopting a time perspective in the planning of DH rollouts. To orchestrate between cities, utilities, building owners, tenants, planners, etc., recognizing the concrete value of new investments and reflecting it in the planning process is essential. The roadmap format is well adapted for this [52]. However, we argue that effective roadmaps should go beyond technical planning and recognize the multiple sustainability dimensions addressed by DH rollouts [53]. As shown in the simulation experiments, the timing of investments determines which value they provide. Priority should be given to measures that reduce investment costs or otherwise alleviate the financing shortfall in the early years of DH rollouts. Also, synergies with building energy retrofits should be identified and proactively managed.

Another result of this study was to demonstrate the highly consequential effect of fossil-fuel bans for heating systems, as are in place in various Swiss cities, for the viability of DH networks. Where such measures are politically feasible, they may prove an essential part of regional decarbonization strategies.

5.3 Limitations and outlook

This study is not without its limitations: first, the presented model is based on the authors' current understanding of the system, which required some subjectivity in the choice of assumptions and simplifications. Also, some important aspects of DH systems were neglected for this study. For example, the current model formulation does not simulate network temperature, which is an essential quantity for the future modernization of DH grids and integration of low-carbon heat sources. Future work may refine the model to also account for temperature reduction [15]. Finally, the use of a synthetic case study rather than a real-world case represents another limitation.

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