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Review article

Feedbacks in district heating systems and transition policies: A systems analysis of net-zero district heating transitions in Europe

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ABSTRACT

Net-zero district heating systems are considered a feasible heating alternative to replace individual natural gas boilers to mitigate emissions in European cities. However, achieving carbon-neutral cities in Europe is a complex affair due to interdependencies in energy transitions. Energy transitions are discussed as products of interdependencies between socio-technical elements within each context, including but not limited to institutions, society, culture, markets, policies, regulations, and technological disruptions/changes. These interdependencies have the potential to transcend beyond the boundaries of technologies, sectors, markets, policies, cities, and even countries which may result in feedback effects.

The presence of feedback effects implies co-evolution: policy-making shapes energy system developments which, in turn, influences policy-making through a range of feedback effects. The objective of this study is to increase knowledge on the implications of feedback effects in energy systems and transition policies by highlighting how they can lead to unexpected systemic consequences, thereby causing inertia or acceleration during the switch out of individual natural gas boilers towards net-zero district heating systems. Understanding the root causes and mechanisms behind district heating transitions could support European policymakers in developing policies that can stimulate the transition toward carbon-neutral cities.

Our results implicate that energy transition governance seldom consists of “simple” fixes as often claimed by popular policymakers or influential actors because each decision impacts the whole system. Different policy sub-goals are indispensable for achieving carbon-neutral cities but they are often indirectly in conflict with each other due to feedback effects. Unless feedback effects in transitions are acknowledged by policymakers, they could work against carbon-neutrality targets due to wrong assumptions and prioritizations of inconsistent policy sub-goals. Therefore, it is essential for policymakers to recognize and comprehend how feedback effects between energy systems and policies are formed and operate.

1. Introduction

In Europe, heating and cooling are roughly responsible for half of the total energy consumption and 36% of energy-related emissions (Thomaßen et al., 2021), and they constitute a significant part of the emission volumes of cities (Loorbach et al., 2010). One of the main causes of this poor performance is the pervasiveness of individual natural gas boilers in the urban heating sector (Toleikyte et al., 2023; Vazquez and Victoria, 2020). Working towards a net-zero future requires replacing individual natural gas-fired boilers (Vazquez and Victoria, 2020) with alternative heating systems that do not rely on fossil fuels across Europe (Kranzl et al., 2022).

District heating systems, along with other alternatives[1] (Vazquez and Victoria, 2020), are considered one of the feasible substitutes for natural

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[1] Heat pumps are considered another key technology for enabling the energy transition towards achieving net-zero cities. Heat pumps are Power-to-Heat solutions which allow enabling flexibility among electricity and heating systems. While they are economically viable on a macroeconomic scale, the high upfront investment costs involved hinder their deployment in the short-to-medium term in many EU countries. The advantage of heat pumps is that they are viable individual and large-scale solutions and can be deployed as soon as the thermal efficiency of the urban area allows (Thomaßen et al., 2021; Simonelli and Zarra, 2019). For example, large-scale heat pumps can be utilized when there is excess energy production from solar and wind energy or industrial processes (European Heat Pump Association, 2022) can be converted to heat for urban and industrial demand.

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gas heating systems because they represent a cost-effective alternative for dense European cities (Zach et al., 2019; Werner, 2017a). District heating systems may utilize combined heat-and-power plants (CHP) and residual heat to increase energy efficiency and reduce fuel consumption (Nciri and Miller, 2017; Rezaie and Rosen, 2012). Moreover, district heating systems can integrate power, heat, thermal storage, and smart systems to increase energy efficiency (Hvelplund and Djørup, 2017; Chittum and Østergaard, 2014), and scale up the utilization of renewables to mitigate emissions (Lund et al., 2014; Millar et al., 2020). The Renewable Energy Directive, which is the legal framework for clean energy in EU countries, stresses the importance of taking prompt action to substitute individual natural gas boilers with (more) sustainable options and considers district heating systems as a significant component of net-zero cities towards 2050 (Vazquez and Victoria, 2020; Kranzl et al., 2022). Although many European countries indeed recognize district heating systems as feasible alternatives and are implementing various policies to stimulate their use (Vazquez and Victoria, 2020), the adoption and utilization of these systems vary notably across the continent (Vazquez and Victoria, 2020). Apart from geographic considerations, this variance can be accredited to social and technical differences between national contexts (Bergek et al., 2015).

In previous research, energy transitions have been discussed as products of interdependencies between socio-technical elements within each context, including but not limited to institutions, society, culture, markets, policies, regulations, and technological changes (Foxon, 2011). Interdependencies have the potential to transcend the boundaries of technologies, sectors, markets, policies, cities, and even countries (Nevens et al., 2013) which may result in so-called feedback effects. Feedback effects occur when interdependent elements in (socio--technical) systems influence each other through a closed chain of causalities, and in turn, themselves (Meadows, 2008). Due to the complexity and sheer magnitude of the energy transition challenges, feedback effects can remain hidden and go unnoticed by policymakers (Grafius et al., 2020), leading to various indirect, and often unexpected, systemic consequences (Bergek et al., 2015) that could accelerate or hinder energy transitions[2] (Gürsan et al., 2023).

The transition governance literature (Edmondson et al., 2019) highlights the continuous systemic interactions between public policies, markets, societal norms, and technological systems (Gürsan et al., 2023) and how such feedback influences policy actors and their subsequent policy-making (Weible, 2018). The presence of feedback effects implies co-evolution: policy-making shapes energy system developments which, in turn, influence policy-making in a bidirectional interdependent manner (Edmondson et al., 2019).

The objective of this study is to provide new insights into the implications of feedback effects for district heating systems and transition policies (Edmondson et al., 2019) by highlighting how they can lead to unexpected systemic consequences, thereby causing inertia or acceleration during the switch out of individual natural gas boilers to net-zero district heating systems (Vazquez and Victoria, 2020; Besharov and Smith, 2014; Greenwood et al., 2011). We zoom in on European countries as they present a wide range of district heating examples with both success and failure stories, allowing us to investigate a range of socio-technical factors across different regions. Understanding the root causes and mechanisms behind district heating transitions could support European policymakers in developing policies that can stimulate the transition towards net-zero cities.

The research question we address here is: *Which feedback effects drive or impede the transition from individual natural gas-fired boilers to net-zero district heating systems?* To answer this question, we conduct a systematic literature review (Myers, 2008) on district heating systems and their governance in Europe. We analyze the collected data by developing qualitative system dynamics (SD) models (Meadows, 2008) to investigate how feedback effects can influence transitions towards net-zero district heating systems in Europe. We explore the complex nature of transitions towards net-zero cities in Europe and the implications of feedback effects in district heating systems and transition policies. Our results implicate that it is essential for policymakers to recognize and comprehend how feedback effects in energy systems, such as district heating systems, and transition policies are formed and operate. Doing so can assist them in governing the (un)intended effects of policy sub-goals and actors' interests during energy transitions.

2. Theoretical background

According to reports from the European Commission in 2021 (Eurostat, 2021a) natural gas, specifically individual boilers (Vazquez and Victoria, 2020), is the prevalent heating choice in Europe except in a handful of countries which use a mix of coal, oil, or renewables for space heating. 59% of these renewables are comprised of bioenergy alternatives (European Commission, 2023) which are still high-carbon sources (e.g. biomass, waste). It is important to mention that biomass presents a different case as opposed to other heating technologies compatible with district heating systems. When combined with carbon capture and storage systems, biomass technologies can achieve negative emissions (IEA, 2023a; Budinis, 2020). The main premise behind the negative emissions is that plants absorb carbon as they grow, and the carbon is captured and stored during combusting biomass (IEA, 2023a; Budinis, 2020). Notably, biomass-coupled carbon storage systems offer the only carbon removal system which also produces energy. Thus, these systems are expected to play an important role in heavy industry or aviation, instead of district heating systems (IEA, 2023a). Although biomass and waste energy provide a smoother transition from fossil combustion technologies, both of these alternatives are expected to face supply restrictions in the coming decades (IEA, 2023a; Edenhofer et al., 2011). District heating systems are among the most cost-effective substitutes for natural gas in dense urban zones with cold climates (Kranzl et al., 2022; Mazhar et al., 2018), especially when the distance between heat production (e.g. Waste-to-Power and Heat) and heat demand (e.g. households, and businesses) is short (Sameti and Haghighat, 2017). Although district heating systems offer significant potential for renewable integration and urban mitigation (Delmastro and Briens, 2023), their share in the European heating sector is only 12% (Kranzl et al., 2022). Most of the district heating systems utilize high-carbon sources for their heat production (Piel et al., 2023). Thus, the total fuel mix in Europe is currently still dominated by fossils and other high-carbon sources (biomass and waste) (Eurostat, 2021b), thereby continuing emissions as depicted in Fig. 1 (Mazhar et al., 2018).

[2] For example, the recent surge of investments in coal power production across Europe has been discussed as a potential consequence of feedback effects (even before the current disruptions to the global natural gas supply chain) (Edmondson et al., 2019). Many researchers argue that lower natural gas prices support the switch out of coal power generation, which is a fair assumption to make since natural gas is a direct competitor of coal with various technical and environmental benefits. In reality, this claim did not work.In recent decades, the expansion of American shale fracking activities reduced the prices of natural gas. If the claim was correct, low natural gas prices would have accelerated the switch out of coal power generation. In reality, low natural gas prices forced American coal industrialists to further reduce the price of coal, and then they exported the already-mined coal to Europe (Gürsan and de Gooyert, 2021). This allowed many European plants to keep operational (Verbong, 2014). In short, the already-extracted coal from the United States spilled over to Europe, and this coal was ultimately utilized elsewhere.Therefore, the relationship between natural gas and coal cannot be washed down to a single factor or a single causality such as price. There are other socio-technical factors (e.g. energy security, market stability, etc.) that influence the switch from coal to natural gas in the power generation sector. For more information about how this feedback effect operates, see (Edmondson et al., 2019).

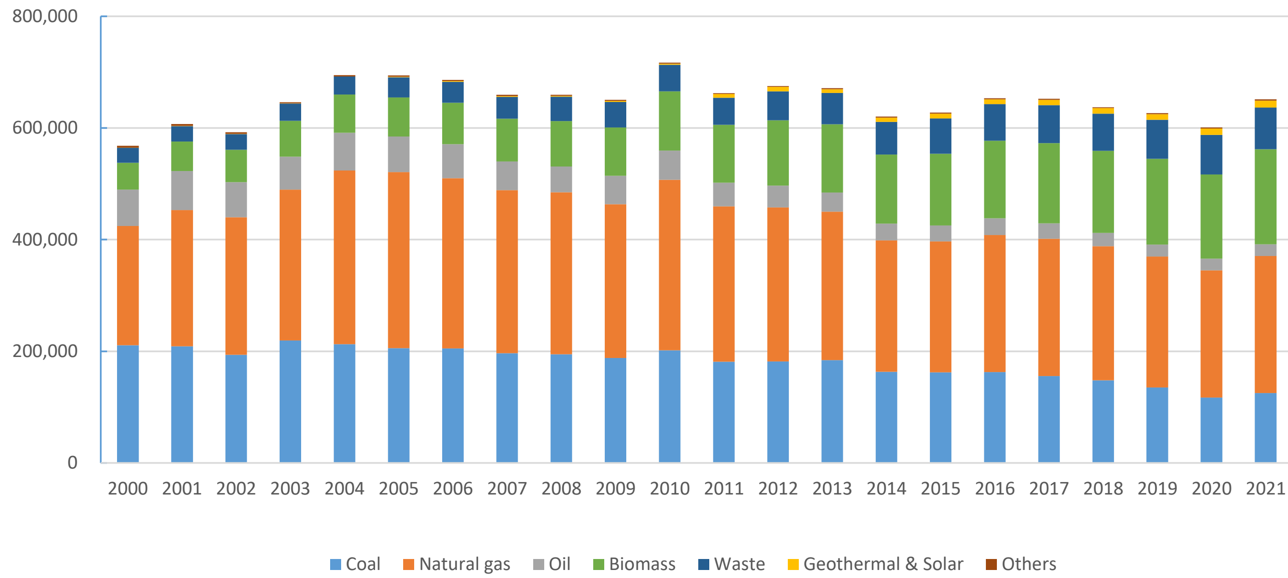

Fig. 1. Annual heat production (in GWh) by fuel source in Europe (Eurostat, 2021b).

2.1. Feedback effects in energy systems and transition policies

A system can be considered a network of interconnected elements that is arranged for a particular purpose. Previous studies (Foxon, 2011; Geels, 2002, 2004) recognize energy systems as socio-technical systems because technologies cannot be separated from their social context. District heating systems can be seen as socio-technical systems by themselves, or as significant components of other systems (Basu et al., 2019) which are governed via complex structures operating at different levels (international, national, municipal, etc.) (Howlett et al., 2017) with different and often conflicting sets of policy objectives (Edmondson et al., 2019). In this research, we highlight district heating systems as the socio-technical system under investigation, which operate under the heat sector, along with a range of synergistic and competing heating systems (e.g. individual natural gas boilers, CHP, etc.).

Notably, the multi-level perspective framework (Geels, 2002) offers an analytical approach for recognizing interdependencies in socio-technical systems (Gürsan et al., 2023; Gürsan and de Gooyert, 2021). The socio-technical systems framework does not only focus on technological artifacts but also the governance arrangements, regulations and policies, user practices, and cultural norms that shape the development and use of socio-technical systems over time (Geels, 2002). At the heart of the framework, energy transitions occur when interconnected elements enable a change in the system configuration (Gürsan and de Gooyert, 2021). Transition governance can be defined as the systematic management of societal transitions towards sustainability (Gürsan and de Gooyert, 2021; Goldthau, 2014). It refers to structures and processes through which policy-making is coordinated for the desired stability or change in social, economic, and environmental systems (Goldthau, 2014). Transition governance is not a static phenomenon but rather involves dynamic processes and networks of actors that span across multiple socio-technical systems (Smith et al., 2005). This intertwined relationship implies that policies and energy systems co-evolve: policies influence energy systems, and energy systems influence policies (Edmondson et al., 2019).

This influence is not a direct one. Instead, policies and energy systems indirectly interact with the policy subsystem (Jordan et al., 2004). Policy subsystems can be conceptualized as the dynamic relationships between actors responsible for policy decisions and interest groups responding to the continuous change in socio-technical systems (Jordan et al., 2004). Typically, policy subsystems function within the broader scope of the socio-technical system(s), and they are impacted by the dynamics and interdependent mechanisms of socio-technical systems (Edmondson et al., 2019). This suggests that a network of feedback effects connects socio-technical systems and policy subsystems together (Edmondson et al., 2019). To give an example, policy decisions (in a policy subsystem) can affect the technological trajectory of socio-technical systems through incentives, regulations, or resource allocation that promote the development of particular (energy) technologies (Goldthau, 2014). In contrast, changes in the socio-technical system(s) (e.g. innovation, user preferences) can lead to reform or change in policy subsystems (Gürsan et al., 2023). In consequence, each policy affects not just its own sub-system but also the entire socio-technical system through a structure of embedded feedback effects (Gürsan et al., 2024).

Consequently, feedback effects can lead to unexpected indirect consequences by (re)configuring causal links across energy actors, sectors, and systems (Edmondson et al., 2019), thereby resulting in acceleration or inertia during transitions (Gürsan and de Gooyert, 2021) through mechanisms such as path-dependency, lock-in, crowd-out, etc (Gürsan and de Gooyert, 2021). Path dependency can be defined here as the extent to which options available today were shaped by past decisions and policies, historical trajectories, and sequences of events, creating a pathway towards certain energy systems instead of others (Sandén, 2004; Dosi, 1982). In energy systems, path dependencies are generally characterized by incremental changes to maintain the quality and reliability of energy services (Loorbach et al., 2010); thus, they are typically associated with inertia in policy-making that favors more mature and often more polluting systems over emerging sustainable alternatives (Unruh, 2000). This is also known as a lock-in (Unruh, 2000). Lock-in refers to a rigid trajectory or pathway that promotes incumbent energy technologies, which are more mature and less sustainable, and crowds out more sustainable emerging energy technologies from the niche level (Unruh, 2002). Crowd-out can be defined as directing investments from a desired technology to another technology due to the lack of maturity (e.g., cost, reliability, efficiency, etc.) of the desired technology (Gürsan and de Gooyert, 2021). Rigid trajectories significantly affect the pace of energy transition by resulting in long-term energy investments in less sustainable but more mature technologies to guarantee the continuity and quality of energy services (Seto et al., 2016).

Increasing our understanding of feedback effects in district heating transitions can support researchers and policymakers in making sense of this complexity, recognizing inertia, and stimulating transitions towards net-zero heating systems (Edmondson et al., 2019). Although feedback effects were recognized in transition governance literature (Edmondson et al., 2019), they were previously investigated primarily over only a single energy system, set of policies, or sector, which ultimately limits the recognition of broad systemic implications (Gürsan et al., 2024). In this research, we use district heating systems as the focal point but also explore competing and synergistic heating systems. We advance the knowledge on feedback effects by exploring how they can influence policy-making in district heating transitions with examples from Europe.

3. Methodology

We investigated the feedback effects during the switch out from natural gas to district heating systems by modeling their implications for net-zero European cities. This research specifically investigated the switch out of individual natural gas boilers to district heating systems which are planned to be coupled with low-carbon heating generation technologies. As summarized in Fig. 2, we conducted a systematic literature review where we collected secondary data from academic literature and reports (Myers, 2008). For the data analysis, we began with open coding to identify the influential variables and interconnections that can influence net-zero district heating systems in cities (Turner et al., 2013). Subsequently, we used axial coding to categorize these influential elements in a hierarchy which resulted in a coding tree. The resulting axial codes involve causal links and feedback effects for building the models. By using this information, we built qualitative SD models (Meadows, 2008), specifically Causal Loop Diagrams, to explore and discuss potential causes for the incremental or accelerated change toward net-zero district heating systems, thereby explaining how feedback effects drive or impede the transition from individual natural gas-fired boilers to net-zero district heating systems. Appendix A includes more information on the data collection and analysis.

3.1. Systematic literature review

For data collection, we conducted two rounds of literature reviews that included research articles and technical, industry, and policy reports (Myers, 2008). In the first round, we investigated 55 review papers with the word sequence "district heat*" in their titles from the Scopus database. We considered a broad range of academic sources to identify influential social and technical elements for district heating systems and transitions. In the second round, we reviewed 28 research papers that contained the word "governance" in addition to "district heat*" in their title from the Scopus database, which yielded insights from 11 different European countries[3] (Vazquez and Victoria, 2020). These countries were identified and discussed by the previous European Union research project WEDISTRICT for district heating systems (Millar et al., 2020). This report identifies the regional opportunities and challenges for 30 different European countries for district heating transitions along with policy suggestions for district heating transitions across the continent.

The two literature review rounds supported the reiterative development of qualitative SD models discussed in this study. In the first round, we searched for influential socio-technical elements and themes that are influential for district heating transitions in the collected qualitative data (Gürsan et al., 2023). After the first round, we drew causal loop diagrams to map out the cooperating and opposing feedback effects that seemed to reoccur in the academic literature. In the second round, we collected data on European policies for district heating transitions across different countries. After the second round, we synthesized the implications of feedback effects in district heating systems and transition policies. Additional reports from international and national sources, which were identified throughout the review rounds, were included in the literature review (Vazquez and Victoria, 2020; Edenhofer et al., 2011; Middlemiss et al., 2020; MBZK and Haag, 2022) in the PRISM Excel file in Appendix A.

3.2. Coding practices for modeling

Structured secondary data can form the empirical foundation to build theoretical models which can synthesize a range of different and often conflicting arguments (Kopainsky and Luna-Reyes, 2008). Such comparative analyses can allow researchers to integrate, recognize, and explain complex mechanisms amongst interconnected policy subsystems and district heating systems in accessible diagrams (Coyle, 2000). Therefore, resulting models can explain a range of opposing and cooperating feedback effects, which ultimately (re)form higher-order feedback structures, to highlight and discuss relevant themes for achieving net-zero district heating systems in Europe.

We structured the secondary data by using the four-step coding approach for building qualitative models (Turner et al., 2013; Eker and Zimmermann, 2016; Akcam et al., 2019; Yearworth and White, 2013). First, we identified open codes inductively to recognize and label influential socio-technical elements for district heating transitions and governance elements for net-zero district heating systems. The first step ended with a list of themes to search again during the second step for building a hierarchy between codes provided by the open coding process. In the second step, we used axial codes to categorize contrasting claims for district heating transitions from different European contexts to identify and explain the cooperating and opposing feedback effects for achieving net-zero district heating systems in Europe. This filtering process allowed us to come up with the final coding tree with the hierarchical relationships between themes. For the third step, we categorized causal relationships from the collected data. For the final step, we reiterated back and forth until we were able to structure (cooperating and opposing) feedback effects in European district heating transitions which we used to discuss the implications of feedback on transition governance (Eker and Zimmermann, 2016). An example of this coding approach is shown in Fig. 3.

3.3. Causal loop diagrams

SD models can represent how system elements are interconnected in feedback structures to explain the systemic influences that are responsible for unexpected behaviors (Meadows, 2008). All system elements are connected to each other by causal arrows. Different annotations on causal arrows clarify the nature of the causality. If the arrow has a "+" sign, this indicates that connected variables change in the same direction. In other words, if the cause increases (decreases) then its consequence also increases (decreases). If the arrow has a "-" sign, this indicates that connected variables change in the opposite direction. In other words, if the cause increases (decreases) then its consequence decreases (increases). If the causal effect occurs with a temporal delay, this is indicated with a delay sign "||" across the arrow (Meadows, 2008).

Closed chains of causalities form feedback loops. Feedback loops represent the causal structure for the feedback effect. The nature of the feedback effect, reinforcing or balancing feedback loops, is denoted as "R" or "B", as shown in Fig. 4. In reinforcing feedback loops, a system element reinforces itself through a closed causal chain (Gürsan et al., 2024). Therefore, these types of feedback effects lead to exponential

[3] WEDISTRICT is a European report on district heating and cooling systems to define the framework for policy development which explains the current situation for district heating and cooling systems in Europe and discusses opportunities and barriers for these systems (Vazquez and Victoria, 2020). The report analyzes 30 European countries and explores the potential challenges for countries with different share of district heating systems. The countries, which we were able to find literature from, were the Netherlands, Denmark, Sweden, the UK, Germany, Norway, Finland, Italy, Austria, Romania, and Belgium in the second round of literature review from the Scopus database.

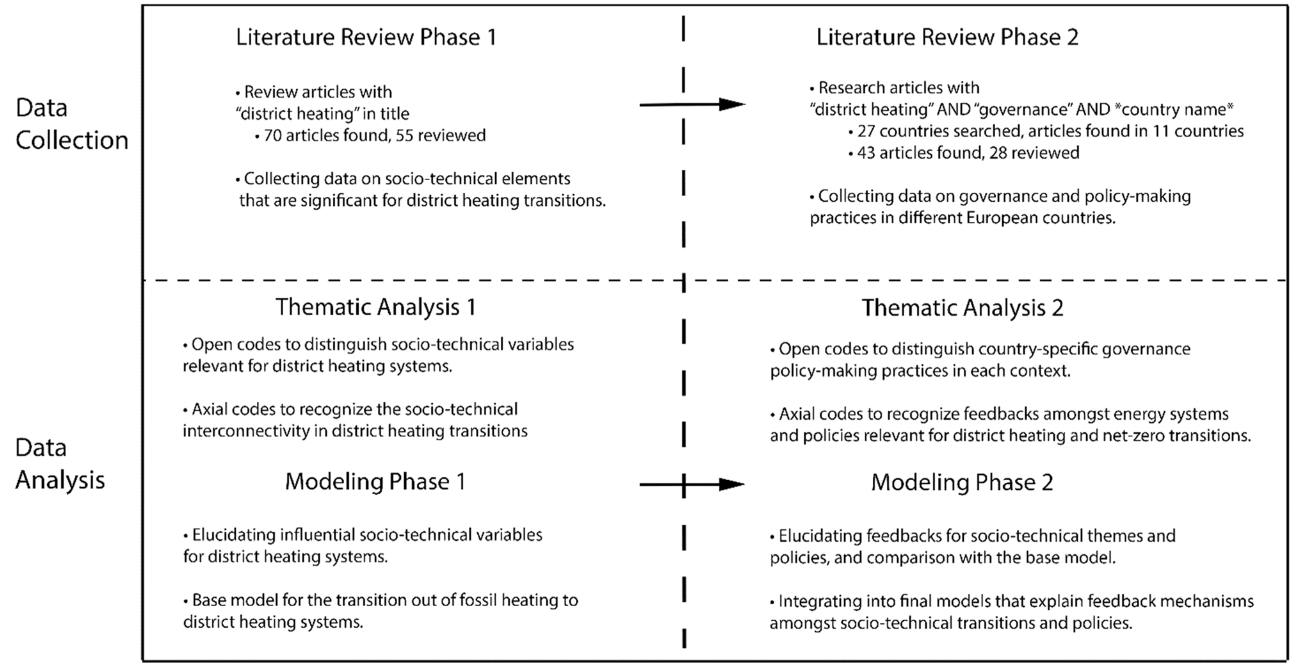

Fig. 2. Methodology chart.

Article	Quote	Open Codes	Axial Codes	Related Feedback/ Theme
Li et al., 2014	"The natural monopoly enjoyed by DH companies has unique characteristics, i.e., customers are tied to only one heating supplier in a DH network. Monopolies in DH markets permit profits and, in the meantime, tend to increase costs for consumers connected to DH systems. However, this does not necessarily mean that DH companies have unshakeable monopoly power, as there are many alternatives on the heating market, such as pellet burners and heat pumps."	Monopoly; competition; energy prices	Renewable Integration > Competition in the heat market	Competition in the heat market (B2 in Figure 8)

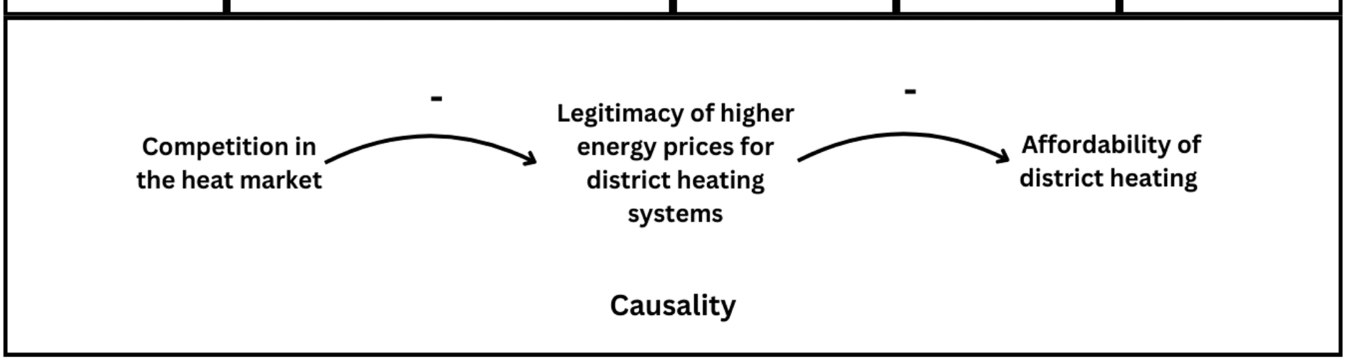

Fig. 3. Coding example illustrating how models were built. More explanations on modeling follow in 3.3.

behavior unless they are balanced by other system elements. To illustrate examples of exponential change, one energy system can swiftly push out another competing energy system from the energy markets by utilizing its advantages (e.g. costs, technical capability, societal penetration, etc.) (Gürsan et al., 2023). For example, district heating systems could not penetrate the UK heat markets due to the abundant natural gas from the North Sea (Hawkey and Webb, 2014; Hawkey, 2014). Balancing feedback effects result in a stabilizing or limiting effect on the system since they pursue an equilibrium (Gürsan et al., 2024). System elements will continue to change until a goal or a limit is reached. When the balancing limit is reached, the system at large can resist further change unless changes are made in the system. To illustrate, limited resources could limit an energy system's development. For example, biomass is being planned to be used in many energy and chemical sectors, including industrial heat, urban heat, aviation fuel, etc (Dutch Parliament, 2019). In consequence, utilizing biomass as an aviation fuel would limit its potential as an urban heat source (Gürsan et al., 2023).

Overall, interconnected elements in the system structure as shown above are constantly influencing each other and thus influence the socio-technical system's behavior. Feedback effects, as shown in these models, operate in similar or opposite directions in tandem. Thereby, feedback effects can (re)form each other as larger sets of feedback effects

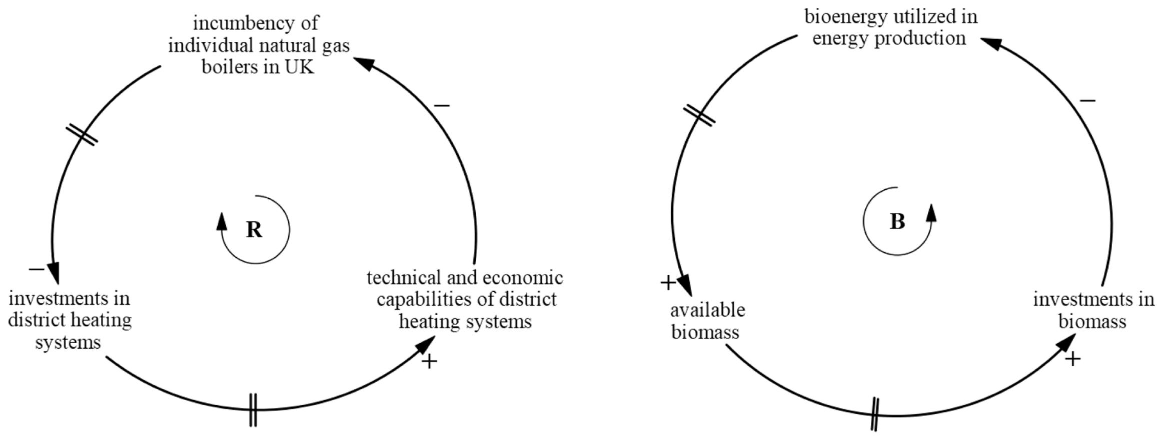

Fig. 4. Example of a causal loop diagram for reinforcing (R) and balancing (B) feedback loops.

operate in tandem. Overall, the resulting behavior of the system emerges as a result of these accumulating simultaneous feedback effects.

For this research, we used qualitative causal loop diagrams (Meadows, 2008), a modeling approach under the umbrella of SD, because they can represent complex issues in understandable models for readers who may not be familiar with modeling (Coyle, 2000). Moreover, they are capable of exploring a broad research scope (often at the cost of depth) which is crucial to recognizing the implications of feedback effects in energy systems and transition policies.

4. Results

In the Results section, we first give an overview of district heating systems. After that, we distinguish and explore three themes recurring during the literature review where feedback effects in energy systems and transition policies can influence the substitution of individual natural gas boilers with net-zero district heating systems. The causal links in these three themes are shown in different colors: energy prices (blue), renewable integration (green), and urban mitigation (orange). Under each theme, we first acknowledge how feedback effects can accelerate or hinder district heating transitions as a stand-alone instrument; thereafter, we discuss how interconnected feedback effects may operate together and thus affect the transition towards net-zero district heating systems in Europe. Finally, we discuss the state of European district heating systems and their opportunities and barriers.

Our models show that policies are typically built in policy silos and designed to achieve heterogeneous sets of policy sub-goals (Veeneman et al., 2009). More often than not, different sets of actors are responsible for different sub-goals (e.g. affordability of energy prices, urban mitigation) which comprise overarching sustainability targets (e.g. net-zero cities). That being said, each policy does not only influence its subsystem but also the whole socio-technical system through interconnected feedback mechanisms. If feedback effects are overlooked, inconsistencies between policies could lead to sets of conflicting policy sub-goals that can ultimately work against each other and net-zero district heating systems (de Gooyert et al., 2016a).

4.1. Overview of district heating systems

Fig. 5,[4,5] shows three components of district heating systems: demand, distribution, and production (Sayegh et al., 2017). The heat produced by (often large-scale central) heating systems is transferred to a series of hot-water pipes which distribute the heat via substations to urban buildings. District heating systems can integrate multiple heat sources which allows switching between fuels or technologies to increase efficiency during energy production (Rezaie and Rosen, 2012; Sayegh et al., 2018) and to deal with peaks and fluctuations in heat production and demand (Guelpa and Verda, 2019). Moreover, district heating systems can increase system flexibility by integrating power, heat, thermal storage, and smart systems (Golmohamadi et al., 2022; Lund et al., 2018). Compatible heating technologies for district heating include but are not limited to (fossil, biomass, and waste) combustion heat-only plants and combined-heat-and-power plants, geothermal, solar thermal panels and plants, residual heat, electric boilers, and heat pumps (Sayegh et al., 2017).

There are five different generations of district heating technologies as portrayed in Table 1 and Table 2[6] (Lund et al., 2014; Sayegh et al.,

[4] For interesting techno-economic analysis on district heating compatible heating technologies, see (Vazquez and Victoria, 2020; Edenhofer et al., 2011; Delmastro and Briens, 2023; Woods et al., 2005; Delmastro, 2022; IEA, 2023b). Detailed research has been done by (Lund et al., 2014; Millar et al., 2020; Mazhar et al., 2018; Lund et al., 2018, 2021; Lake et al., 2017; Sarbu et al., 2022; Arabzadeh et al., 2020; Boldrini et al., 2022) which discusses district heating systems, their compatible heating technologies, and future opportunities.

[5] The graphical elements used in this figure are free to use with attribution to the FlatIcon.com website. Attribution links for all pictures used in this figure can be found below.https://www.flaticon.com/free-icon/pipe_259625https://www.flaticon.com/free-icon/water-pipe_4524481https://www.flaticon.com/free-icon/factory_1908006https://www.flaticon.com/free-icon/geothermal-energy_542428https://www.flaticon.com/free-icon/sun_2354809https://www.flaticon.com/free-icon/air-source-heat-pump_10483135https://www.flaticon.com/free-icon/heater_1677076https://www.flaticon.com/free-icon/storage-tank_10556461https://www.flaticon.com/free-icon/heat-exchanger_10483223https://www.flaticon.com/free-icon/buildings_2942076https://www.flaticon.com/free-icon/factory_699404https://www.flaticon.com/free-icon/pump_2299225https://www.flaticon.com/free-icon/house-outline_25794https://www.flaticon.com/free-icon/co2_11931384https://www.flaticon.com/free-icon/server_2316109https://www.flaticon.com/free-icon/meter_6031388https://www.flaticon.com/free-icon/smart-grid_4757304https://www.flaticon.com/free-icon/boiler_8789783https://www.flaticon.com/free-icon/radiator_3999685https://www.flaticon.com/free-icon/element_7100327

[6] **Generation of district heating technologies**

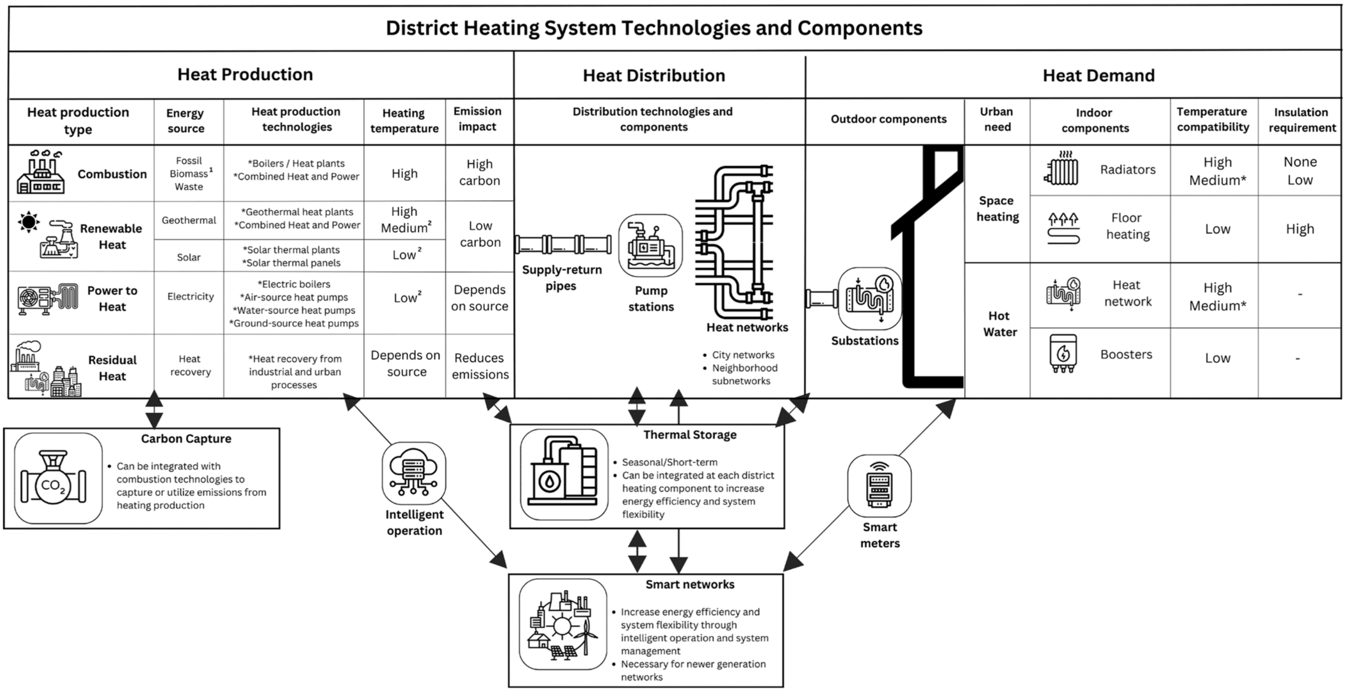

Fig. 5. Detailed representation of interconnected district heating components and technologies. 1: Biomass can achieve negative emissions when combined with carbon capture and storage systems (IEA, 2023a). 2: Medium or low temperature heating options would require thermal insulation before deployed, or they can be used to complement other heating technologies in under high temperature regimes.

Table 1
District heating generations and technological innovations, adapted from (Lund et al., 2014).

Generation	Time period	Temperature regime	Operating temperature	Energy carriers	Added technologies at each generation
Proto	Before 1880	-	-	Hot-water	* Geothermal
1st	1880–1930	< 200 C^o	Ultra High	Steam	* Heat plants (coal, waste) * Centralized thermal storage
2nd	1930–1980	> 100 C^o	Ultra High - High	Pressurized hot-water	* Combined heat and power (coal, waste)
3rd	1980-Current	< 100 C^o	High	Hot-water	* Combined heat and power (oil, gas, biomass) * Residual heat * Solar thermal plants
4th	2010-Current	< 70 C^o	High - Medium	Hot-water	* Combined heat and power (waste) * Centralized heat pumps * Seasonal storage
5th	2020-current	< 40 C^o	Low - Ultra Low	Hot-water	* Two-way heat/cold transfers * Cold storage * Individual heat pumps * Individual thermal storage

2017). Over the years, district heating networks have become more efficient and moved to lower-temperature water regimes in each generation (Pellegrini and Bianchini, 2018). Europe has a range of heat networks that span across second- and fourth-generation systems in different regions. Third-generation heat networks are the most common across Europe and the world. Third-generation networks operate at temperature regimes below 100°C. Fourth-generation networks can operate at temperature regimes below 70°C. Fourth-generation heat networks can utilize medium or low-temperature heat from smaller scaled renewable heating technologies across the city. Fifth-generation networks operate at ultra-low or low temperatures; thus they can satisfy both the heating and cooling needs of citizens (Rezaie and Rosen, 2012). Fifth-generation networks enable other heat and cold producers and prosumers to feed into the grid (e.g. selling their excess energy back to the grid) which in turn increases the share of renewable generation in heat networks (Pellegrini and Bianchini, 2018) That being said, fifth-generation networks are still new and untested in larger scales (Vazquez and Victoria, 2020).

This generation choice is not a black-and-white decision. The more a district heating system presents fourth-generation characteristics (e.g. operation temperature, available low-carbon heating systems), the better they can integrate renewable energy and increase system flexibility (Vazquez and Victoria, 2020). Reducing the operation temperature of the heat network calls for insulating the urban environment accordingly and choosing the compatible equipment and infrastructure for the future of the district heating network (e.g. floor-heating, pipes, etc.). To illustrate an example, large-scale heat pumps can generate heat for district heating networks which are supplied by electricity from solar and wind energy. If and when intermittent energy cannot be utilized in the electricity market, it can be transformed and stored as heat in the district heating networks (Vandermeulen et al., 2018). Therefore, district heating systems develop flexibility and integration opportunities among electricity and heating systems (Lund et al., 2021). Currently, most European district heating systems use third-generation heat networks with high-carbon sources such as natural gas, coal, oil, biomass, and waste as well as some low-carbon sources such as solar energy and heat pumps (Vazquez and Victoria, 2020). Achieving net-zero targets with district heating systems would call for replacing individual natural gas

Table 2
Heat generation type by technology (Lund et al., 2014; Mazhar et al., 2018; Lake et al. 2017).

Heating Technology Type	Generation compatibility	Generation type	Notes
Combustion	3rd, 4th	Baseload Dispatchable for peaks	Favored due to their cost-effectiveness, operational convenience, and unvarying energy generation.
Power-to-Heat	3rd, 4th	Dispatchable for baseload support and/or peak*	Heat pumps typically provide operate on lower temperatures. Therefore, they cannot provide the baseload heat demand for 3rd generation networks. They can be dispatched when electricity prices are favorable. Notably, they can be coupled with intermittent power systems (solar, wind, etc.) to produce heat when there is a surplus of power.
	5th	Baseload Dispatchable for baseload support and/or peaks*	
Solar	3rd, 4th	Dispatchable intermittent for baseload support	Solar systems need to cooperate with other systems due to intermittent heat generation from solar.
	5th	Dispatchable intermittent for baseload support	
Geothermal	3rd, 4th, 5th	Baseload Dispatchable for baseload support	Geothermal is the only renewable source that can produce heat unvaryingly, similar to the fossil combustion. Furthermore, they can scale up by itself to produce enough heat for a city, or a country in Iceland's case. However, they are dependent on local availability and have significant risks concerning drilling processes.
Residual heat	3rd, 4th, 5th	Dispatchable intermittent for baseload support	The heat is produced only when the industrial or urban process is active and thus residual heat provides intermittent heat. As a result, they need to cooperate with other systems to provide the baseload demand.

boilers and integrating more renewable energy in district heating systems (Kranzl et al., 2022).

4.2. Energy prices

Fig. 6 explores feedback effects related to energy prices in the competition between district heating systems and natural gas (Gürsan et al., 2024). Citizens would be more inclined to switch from individual natural gas boilers to district heating when they perceive district heating as a cost-effective option (Gürsan et al., 2024). In dense urban areas, district heating systems can be a cost-effective alternative for individual natural gas boilers due to the economies of scale effect, as depicted in loop Fig. 6.**R2** (Zach et al., 2019). Economies of scale refer to the fact that the cost of deploying the heat network does not increase as much as the increase in the number of district heating users. This ultimately decreases the required costs per network connection as the heat network expands[7] (Zach et al., 2019). With larger heat networks, it is easier for energy companies to build a business case for healthy long-term returns and to provide affordable utility contracts and transition offers for citizens (Gürsan et al., 2024). This helps scaling up the heat network even further (Woods et al., 2005). Furthermore, the heat production capacity needs to expand in tandem with the heat network to satisfy the heat demand (Gürsan et al., 2023). This results in an economies of scope effect (Panzar and Willig, 1981). Economies of scope can be defined as systemic economic benefits between heat networks and compatible heating systems such as reduced fuel consumption and energy costs or increased efficiency and flexibility (Guelpa and Verda, 2019; Djurić Ilić, 2021), also portrayed in Fig. 6.**R2**.

Overall, natural gas and district heating systems compete with each other to satisfy the urban heat demand, as shown in two reinforcing feedback loops Fig. 6.**R1** and Fig. 6.**R2** operating in opposite directions. Fig. 6 implies that when a critical number of district heating users is reached, district heating systems become a relatively cost-effective alternative, and more citizens are willing to switch from individual natural gas boilers. This reinforces a further increase in cost-effectiveness, the number of district heating users, the development (or expansion) of heat networks, and investments in compatible heating systems (Lake et al., 2017). These synergistic economic feedback mechanisms can allow cities to easily reach the required number of district heating users to further expand and scale up the heat network and production level (Zach et al., 2019). This is reflected in Nordic examples, where district heating systems do not need incentives or forced zoning regulations anymore (Sovacool and Martiskainen, 2020; Johansen and Werner, 2022) because they already became considerably cost-effective due to this positive economic feedback.

On the other hand, some authors (Gürsan et al., 2024; Li et al., 2015; Davis and Hausman, 2022) argue that certain price mechanisms could impact the pace of replacing individual boilers. Legacy costs refer to the increase in operational or maintenance costs when a system is shared by a decreasing number of users due to the replacement of that system (Davis and Hausman, 2022). As more citizens abandon natural gas as an energy source, the remaining natural gas users may face higher utility bills. This is because fewer households are responsible for paying the fixed maintenance and operational costs of the natural gas infrastructure (Lavrijssen and Vitéz, 2021). Meanwhile, energy companies may face losses as their fixed costs remain almost constant, but the natural gas market gradually contracts, and their investments for transition gradually increase (Davis and Hausman, 2022). A similar effect called a utility death spiral was identified for district heating systems (Gürsan et al., 2024) and the electricity sector (Felder and Athawale, 2014). This effect may already started to occur since transition costs are shown as one of the main culprits for the recent increases in heat prices, along with uncertainties in the global energy markets (Cevik and Ninomiya, 2022; André, et al., 2023). In recent years, these increasing heat prices resulted in significant subsidization for household energy costs in Europe (Zachmann et al., 2021).

High prices in natural gas could create transition barriers for households with energy-poverty challenges. Although higher gas prices

[7] Installing the primary supply-return pipelines represents the largest cost item for district heat networks. Connecting individual apartments or buildings to the network is a relatively smaller investment (Zach et al., 2019). Thus, the investment cost per network connection keeps decreasing significantly as the number of district heating users increases, reinforcing the cost-effectiveness of the heat network non-linearly. In turn, this incentivizes more users to connect to the heat network. Feedback loops can also work in the opposite direction: district heating systems cannot become cost-effective unless a critical number of users is reached for each heating zone.

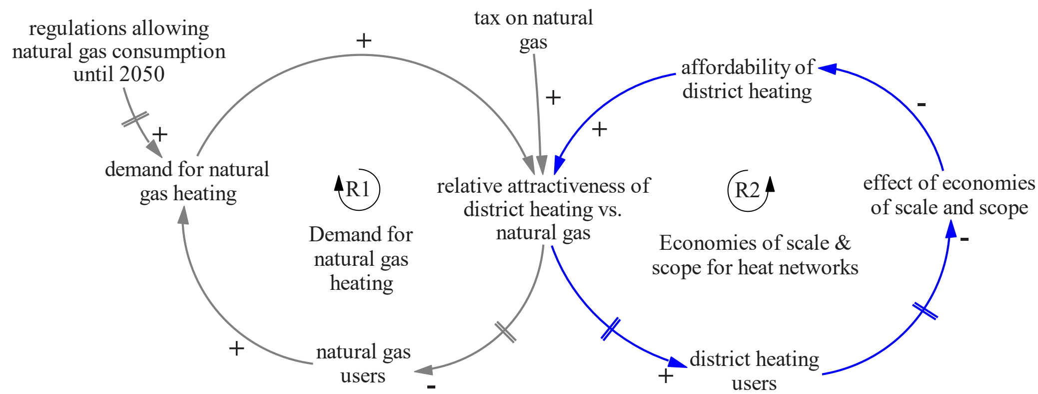

Fig. 6. District heating systems can form positive economic and technological feedback loops, which can scale district heating systems further. This concept model is adapted from (Gürsan et al., 2023; Gürsan & de Gooyert, 2021).

would motivate citizens to consider other heating alternatives in the long term (Kranzl et al., 2022), unaffordable energy prices could impair households with energy-poverty challenges disproportionately in the short-to-medium term (Bouzarovski et al., 2020). This could dissuade citizens and households with energy-poverty challenges from investing in a new system (Middlemiss et al., 2020), as shown in the feedback loop Fig. 7.**B1**. Subsequently, increasing energy natural gas prices could strengthen the effect of energy poverty by keeping energy-poor households dependent on natural gas heating for longer (Middlemiss et al., 2020), thereby prolonging the use of natural gas and constraining the switch to alternative heating systems including district heating (Gürsan et al., 2024).

Soaring natural gas prices legitimized benchmarking prices for alternative heating sources at higher levels across Europe (European Comission, 2022). On the one hand, price caps for alternative heating prices protect customers against volatile disruptions in energy markets. On the other hand, high-leveled price caps, caused by high natural gas prices, could give energy companies the incentive to take advantage of cost-transparency challenges in district heating systems (Li et al., 2015) to inflate their costs for maximizing profits, as shown in Fig. 7.**B2**[8], which implies a spillover effect. Moreover, 27% of the district heating networks in Europe today are still coupled to centralized natural gas heating systems (Kranzl et al., 2022), which makes the price of some heat networks directly dependent on natural gas prices. Ultimately, high-priced natural gas has a spillover effect on the price of district heating services as a consequence of natural gas-heated networks and the legitimacy of higher of higher prices as shown in Fig. 8.B1[9].

Overall, Fig. 7 raises an interesting conundrum (Gürsan and de Gooyert, 2021). On the one hand, affordable natural gas prices might demotivate the switch to district heating systems since European citizens are allowed to use their existing gas heating equipment as long as it remains operational and up to 2050 (Kranzl et al., 2022). On the other hand, the high prices of natural gas, due to increasing taxes (Bouzarovski et al., 2020), global uncertainties (Cevik and Ninomiya, 2022), transition costs (André, et al., 2023), and utility death spiral (Gürsan et al., 2024), could legitimize higher prices for district heating systems through the fossil price spillover mechanism, increase the financial burden on citizens and households with energy-poverty challenges, delay the energy transition due to these financial challenges (Middlemiss et al., 2020), and ultimately work against cost-effective heat networks.

4.3. Renewable integration

This subsection explores the feedback effects concerning the integration of renewables in district heating systems. Achieving net-zero cities will require a patchwork of dispersed urban energy solutions to operate together (Lavrijssen and Vitéz, 2021). European cities must, therefore, investigate the potential for all alternative energy sources in their areas to determine the most practical approach for decarbonizing the urban heat sector (Kranzl et al., 2022). One of the main benefits of heat networks is that they can connect low-temperature renewable sources across a city and thus create small-scaled heat islands where generated renewable heat is utilized efficiently (Lavrijssen and Vitéz, 2021). In doing so, district heating systems can present a significant opportunity to integrate and scale up renewable heat production in cities (Lavrijssen and Vitéz, 2021).

Although district heating systems can offer such opportunities for urban transitions and future energy systems, the integration of renewable energy still depends on several socio-technical factors. Unlike electricity or natural gas users in Europe, district heating users cannot switch heat providers. This is because heat network operators are often vertically integrated energy suppliers (Lavrijssen and Vitéz, 2021) who claim the license for district heating sales in that specific region (Hawkey and Webb, 2014). As a result, heat networks are often natural monopolies (Rezaie and Rosen, 2012) which operate under certain price regulations for fair energy prices (Lavrijssen and Vitéz, 2021). Citizens, in some cases, can choose to connect to the district heating network, but they can seldom choose their district heating supplier. Once the decision is made, district heating users are often locked into long-term contracts with no viable alternatives to switch back to, or have no say in the energy source for heat production (Lavrijssen and Vitéz, 2021). Subsequently, network operators can capitalize on heat licenses to create market and regulatory barriers for other heat competitors (other network operators, heat suppliers, or prosumers) to protect their advantageous position in the heat market and their profits from district heating sales (Hawkey and Webb, 2014), as shown in Fig. 8.**B1**. In low-

[8] In a cost-plus-profit pricing approach, often seen in regulated heat markets, energy companies are encouraged to inflate their costs. In the marginal cost pricing approach, often seen in deregulated heat markets, energy companies may be less motivated to invest in and maintain heat networks since they stand to gain less compared to the cost-plus profit pricing approach (Li et al., 2015).

[9] Spillover is a broad concept that refers to interconnections between emission-reduction policies, industry, infrastructure, market organization, and technology implementations (Gürsan and de Gooyert, 2021). In this example, the high price of natural gas "spills over" to alternative heating prices, ultimately pushing district heating prices to higher levels. Gas-coupled heat networks are not specifically shown in the model because this is also an example of fossil spillover due to the co-dependent operation of heat networks with natural gas. This effect is aggregated in the **B2** feedback loop of Fig. 8. Furthermore, this spillover effect is not only limited to the heating sector. The electricity price, which influences the cost of heating by heat pumps, is also strongly related to the natural gas price due to the design of the electricity market where the strike price is set by the most expensive producer in the market in Europe.

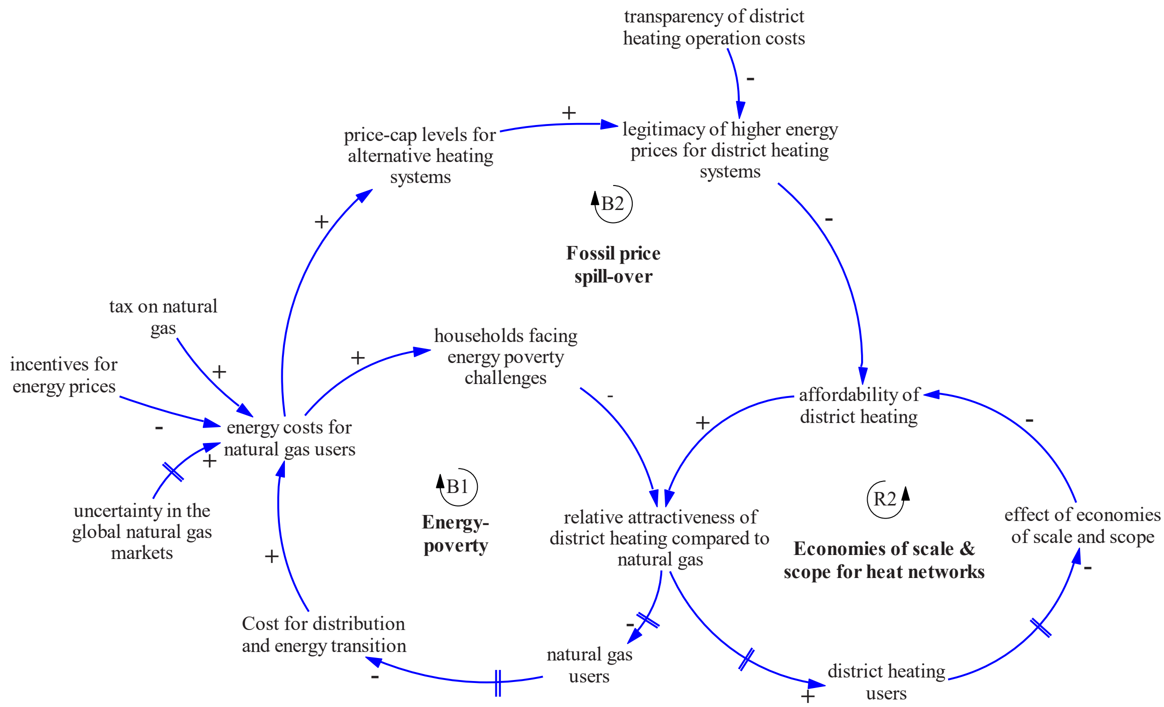

Fig. 7. Price feedback mechanisms that can slow down the replacement of natural gas heating. Feedback mechanism B1 adapted from (Gürsan et al., 2023).

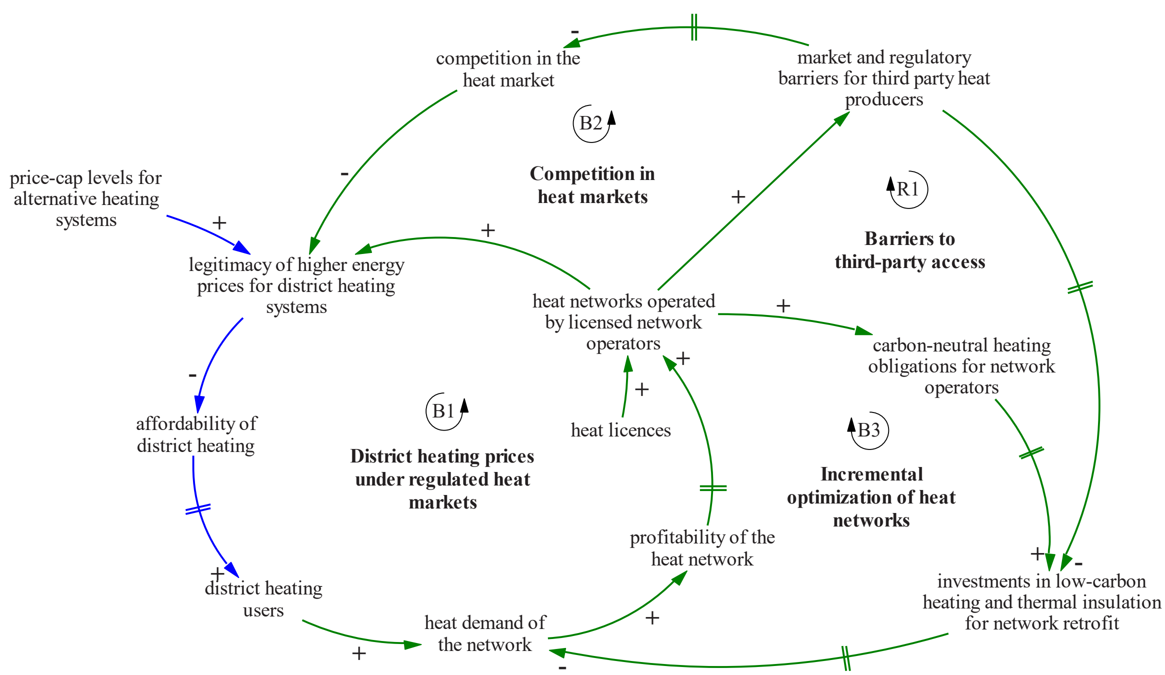

Fig. 8. Renewable integration depends on unbundling and deregulating the heat market, as shown in green.

or zero-carbon heat networks, the heat is supposed to come from different sellers due to the smaller scales of the renewable heating systems. This implies that barriers against third-party access could crowd out low-carbon alternatives[10] by blocking network access for competing heat suppliers, inhibiting production- and cost-efficiencies due to the competition in heat markets, and thus negatively influencing district heating prices, as shown in Fig. 8.**B2** (Lavrijssen and Vitéz, 2021).

Low-carbon heating alternatives necessitate insulating the built environment, renovating heating equipment in households, and insulating or replacing distribution pipes in heat networks (Pellegrini and Bianchini, 2018; Sarbu et al., 2022). Therefore, network expansions are often made in neighborhoods where buildings share homogenous technical characteristics, such as insulation levels, required distribution pipes, heating equipment at households, required water regimes, and heat demand (Lund et al., 2018). On the one hand, insulating the heat

[10] Crowd-outs occur if investments into a desired (sustainable) energy system are displaced by another (incumbent) system because the desired system cannot compete with the other (incumbent) system (Unruh, 2000).

network and built environment reduces the city's heat demand gradually and prepares the heat network for low-temperature regimes and smaller-size renewable heating systems. On the other hand, the gradual decrease in the urban heat demand could also diminish the revenues from heat sales as the heat network becomes more efficient (Gürsan et al., 2024) or the heat demand is compensated by third parties. This implies a split-incentive issue[11] between network operators and other heat actors, as shown in Fig. 9. To achieve net-zero networks, network operators have to decarbonize their energy operations and risk diminishing revenues while energy customers reap the benefits of reduced energy consumption and third parties could crowd out energy companies due to low-cost renewable heat. This implies friction between network operators and other actors if the pricing scheme (Li et al., 2015; Liu et al., 2019a) is dependent on energy consumption.

Although carbon-neutrality regulations for energy companies push towards retrofitting heat networks and investing in renewable heating as shown in Fig. 8.**B3**, network operators still stand to gain if the network retrofit (Paiho and Reda, 2016) and third-party access are delayed (Lavrijssen and Vitéz, 2021). Leaving the decarbonization responsibility to a single actor, namely licensed network operators, restricts the potential niche-level developments from other heat suppliers, grassroots movements, and prosumers, thereby limiting the potential renewable integration in district heating systems (Hawkey and Webb, 2014; Lavrijssen and Vitéz, 2021). Restricting third-party access, deregulation, and unbundling could result in incremental optimization by network operators (Unruh, 2000) instead of a radical transformation which is needed to scale up the utilization and integration of renewable heating in cities (Moilanen et al., 2023).

4.4. Urban mitigation

Feedback mechanisms also affect urban mitigation during district heating transitions. Although a successful integration of renewables in heat networks can notably mitigate urban emissions, achieving this outcome is dependent on the technical readiness of the built environment and heat network as well as on the market and regulatory structures that support the development of these capabilities. Operating heat networks at low temperatures necessitates insulating the built environment, retrofitting distribution pipes, renovating household heating equipment, and scaling up renewable alternatives across the city (Lund et al., 2018). Achieving these steps, however, depends on breaking out of the incremental optimization trap for heat networks as shown in Fig. 10.

District heating systems may pose energy security challenges when the single licensed heat provider cannot match the sustainable heat demand from an increasing number of users in an expanding network unless a much wider range of heat sources from third parties is allowed (Millar et al., 2020). Existing heat networks are often supplied from one large (or a limited number of) fossil heat source(s) by a single licensed network operator (Kranzl et al., 2022; Lavrijssen and Vitéz, 2021). If sustainable heat generation cannot satisfy the urban heat demand (notably, the share of renewables for heating and cooling in 2020 in the EU was only 23.1% (Piel et al., 2023)), Fig. 10.**R1** implies that there might be a strong path-dependency towards utilization of fossil fuel-based heating. Energy companies can capitalize on the technical maturity, historically strong political network, and lobbying power of these systems to maintain their market share (Hvelplund and Djørup, 2017). Although network operators must follow plans to decarbonize their energy operations, as shown in Fig. 10.**B1** (Kranzl et al., 2022), challenges to energy security in Fig. 10.**R1** might legitimize network operators to maintain investments in fossil heating systems. These investments may happen at the expense of gradually developing renewable alternatives which cannot fully satisfy the urban demand at that time (Paiho and Reda, 2016). This may, in turn, reduce the pace of the urban transitions as required investments for low-temperature networks. are crowded out by high-carbon heating systems for the sake of energy security.

Cogeneration was the leading factor for the high adoption rates of district heating systems where (sustainable) fuel was abundantly available (Sovacool and Martiskainen, 2020). Biomass and waste CHP plants show great potential because they can replace centralized fossil heating systems in heat networks without extensive investments (Honoré, 2018) and be coupled with carbon capture systems to mitigate emissions from combustion processes (Eliasson et al., 2022). However, biomass and waste alternatives are projected to face scarcity challenges in the future since there are simply not enough of these resources to satisfy the growing demand (Kranzl et al., 2022), as shown in Fig. 10.**B2**. Therefore, European countries may have to compete with each other to import limited sustainable fuels, which raises uncertainties around sustainable cogeneration in the future. If the urban heat demand cannot be matched with sustainable cogeneration, this could create the legitimacy to invest further in fossil CHP for energy security.

At the same time, overinvestment in high-carbon heating systems might also activate mechanisms that can lead to inertia during urban transitions. Infrastructure projects are long-term investments, and energy companies seek to generate stable profits over decades (Heath and Read, 2014). Thus, overinvestment in high-carbon heating systems, due to their maturity and scalability, may facilitate the utilization of high-carbon sources and thus urban emissions in the following decades (Gürsan and de Gooyert, 2021). Consequently, a high level of coupling between combustion technologies and the urban heat sector could necessitate the deployment of carbon capture and storage/utilization systems (Gürsan et al., 2024). This may, in turn, crowd out other mitigation investments (Eliasson et al., 2022; Janipour et al., 2021), specifically low-carbon heating systems (Dutch Parliament, 2019), and thus negatively influence the readiness of heat networks for lower-temperature regimes. In contrast, early phasing out of overinvested combustion technologies could result in stranded assets, activate contract-breach clauses, and sunk costs, which could ultimately cost more to society (Heath and Read, 2014). Overall, scaling up heat networks with high-carbon systems could reduce the pace of renewable integration due to incremental optimization, prolong the use of high-temperature systems, and result in a high demand for carbon capture systems (Unruh, 2000, 2002). Unless an urban roadmap for future energy supply and demand is in place, current heat networks might be locked in on third-generation systems coupled with carbon capture systems since they might not have the capability of integrating lower-temperature heat sources[12] (Gürsan et al., 2024).

4.5. The current state of European district heating systems

In this subsection, we explore how district heating transitions were influenced in different European regions by feedback effects. We give examples from Nordic, Baltic, Eastern European, Central European, and Southern European countries to explain systemic opportunities and barriers for net-zero district heating systems caused by feedback effects. Countries with a large share of district heating systems (>50%) such as Nordic and Baltic countries (Vazquez and Victoria, 2020) utilize a mix of biomass, waste, fossils, and renewables. The countries in this category have been consistently increasing their heat production and heat

[11] Split-incentive issues are often discussed for property owners and tenants facing thermal insulation challenges in the built environment (Melvin, 2018). Property owners need to invest in thermal insulation while tenants benefit from these investments. Fig. 9 implies that a similar effect might be relevant for net-zero networks as well.

[12] Lock-in can be defined as a rigid trajectory that characteristically favors incremental change in available (high-carbon) energy systems and crowds out other emerging (sustainable) options (Seto et al., 2016).

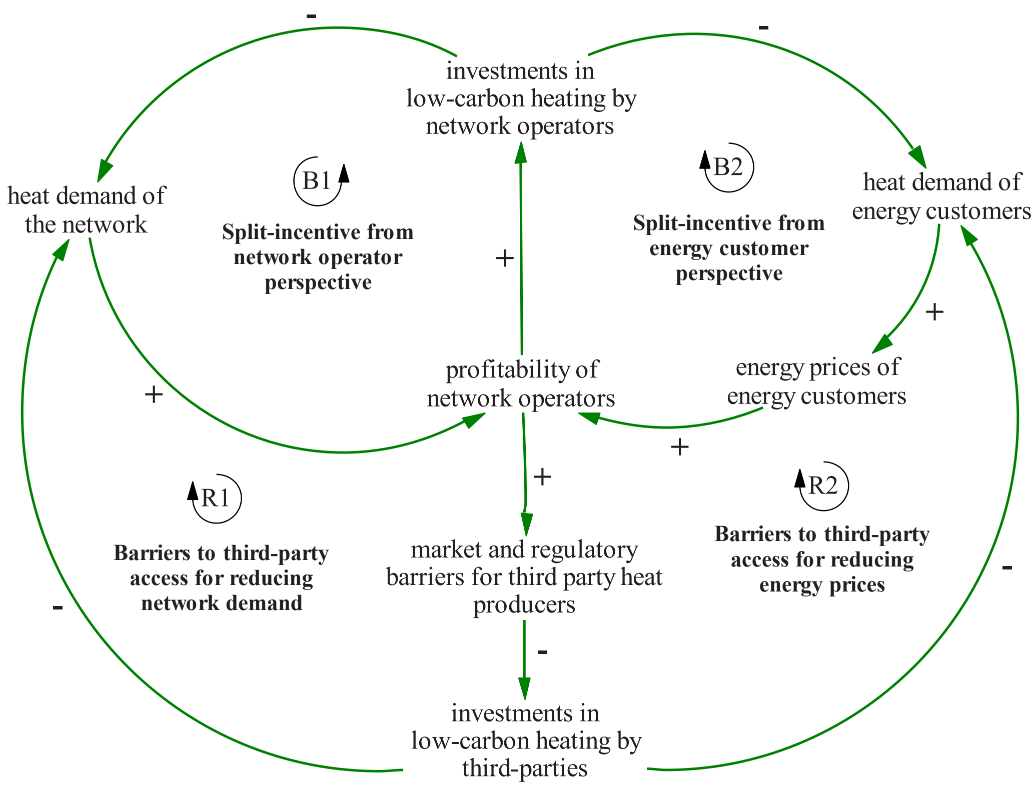

Fig. 9. Split incentives force multiple actors to compete with each other to protect their interests.

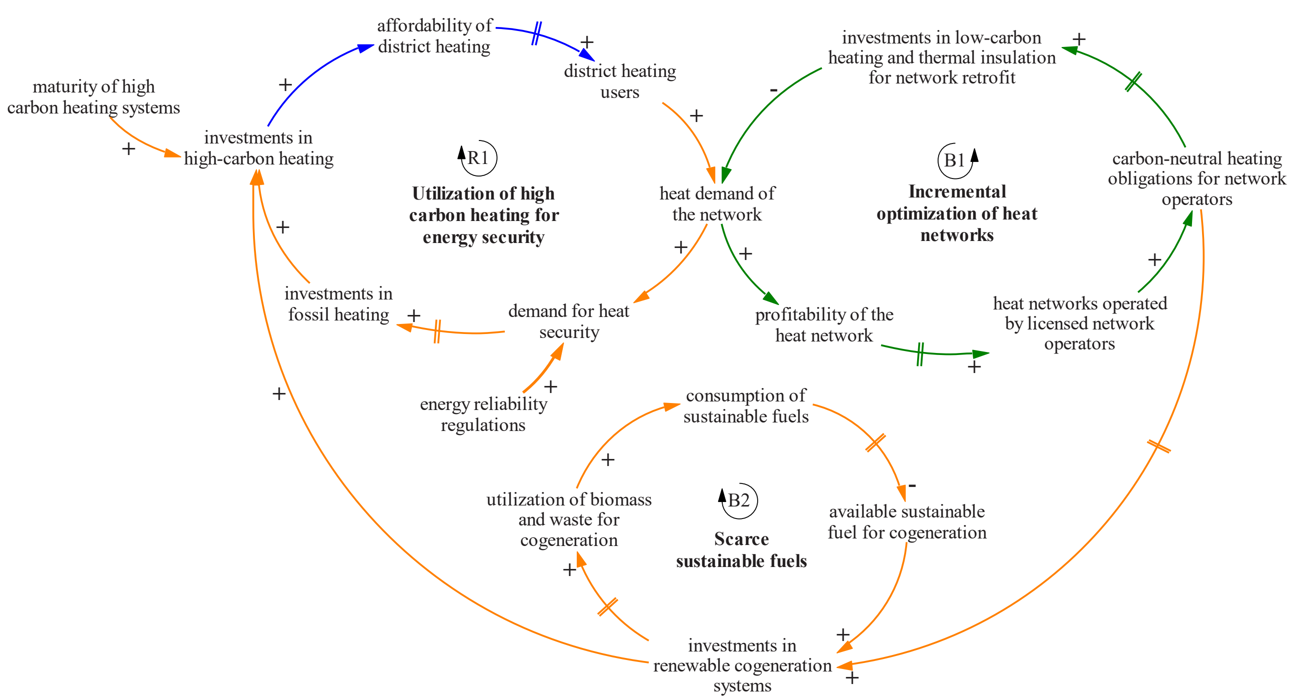

Fig. 10. Mitigation requires breaking the incremental optimization cycle for heat networks shown in orange.

network capacity in the last decades. During the oil crisis in 1973, Nordic countries were highly dependent on oil, at a high level of 92% for Denmark and 64% for Sweden (Our World in Data, 2023). This dependency pushed Danish policymakers into drafting the first-ever Heat Act in Europe in 1979 (Sovacool and Martiskainen, 2020). This heat act gave local municipalities the authority to establish mandatory zones for heat networks and invest in local decentralized cogeneration systems, especially if local biomass fuel from forestry industries was available. The efficiency of CHPs and municipal interventions allowed an accelerated adoption of district heating systems in Denmark which inspired neighboring countries to develop similar heat acts (Nciri and Miller, 2017; Hawkey and Webb, 2014; Sovacool and Martiskainen, 2020) due to economies of scale and scope feedback effect in Fig. 6.**R2**.

In Denmark and Sweden, local municipalities were already deeply involved in district heating and heat production investments for decades before privatization discussions began (Vazquez and Victoria, 2020). Municipal energy companies had a long-standing citizen engagement and price dialogs to win the necessary support for the next election, which ensured low energy prices in this region (Sovacool and Martiskainen, 2020; Werner, 2017b). Low energy prices meant stable long-term revenues for municipal energy companies, which, in turn, resulted in better long-term loan offers for scaling district heating systems. The culture of citizen management was ensured after the liberalization of the energy markets in Denmark and Sweden, because municipal energy companies stayed, directly or indirectly, in the management of heat network companies (Vazquez and Victoria, 2020). This ensured the stability of affordable energy prices, which further reinforced investments in the integration of local renewable sources and urban mitigation before the liberalization of the energy markets in the 1990s. This implies that citizen management could ensure affordable prices, and activate economies of scale, thereby counteracting the negative effects of energy-poverty feedback in Fig. 7.**B1**. Currently, Denmark has the highest renewable heat production for heat networks in the world with 65% as a result of their cross-cutting pilot projects in district heating systems (Sovacool and Martiskainen, 2020) (intermittent power generation coupled heat pumps, fifth-generation heat networks, solar thermal plants, etc.). The challenges for the Nordic, as well as some of the Baltic countries, are the high utilization of biomass and waste cogeneration (Mazhar et al., 2018) as shown in Fig. 10.**B2** and market saturation for district heating services (Vazquez and Victoria, 2020); thus, the next step would be replacing cogeneration coupled district heating systems with renewable alternatives since cogeneration fuels (biomass, waste) will have scarcity issues in the future as the growth in the district heating market stagnates and reduces the economies of scale and scope (Vazquez and Victoria, 2020).

Baltic and Eastern European countries, which have a high and a medium share of district heating systems (10–50%), typically coordinated state-led investments in a range of second and third-generation heat networks under the Soviet Union to combat the oil crisis. District heating systems have scaled fast due to the abundance of coal in Eastern Europe and biomass in the Baltic regions (Vazquez and Victoria, 2020). Scaling up infrastructure projects with cross-sectoral implications, such as district heating systems, has been easier to achieve in the coordinated market economies of Soviet countries because of the cooperation and information-sharing amongst decision-makers and departments in municipalities and central government (Hawkey and Webb, 2014). After the liberalization of the energy markets, these second- and third-generation heat networks in Eastern European and Baltic countries were privatized to vertically-integrated energy companies which now face a serious network retrofit challenge due to the high dependency on coal or biomass consumption (Vazquez and Victoria, 2020). The high levels of investment for the retrofit may present barriers to energy companies in these regions as they will be forced to balance between operational costs of natural gas and investments in alternative heating systems such as district heating. Thus, it is essential to create regulatory frameworks which would incentivize retrofitting the heat networks. Failing to scale renewable heating capacity in these regions might result in a lock-in to individual boilers as well as existing district heating systems coupled with fossils as shown in the utilization of high-carbon heating feedback effect in Fig. 10.**R1** and incremental optimization feedback in Fig. 10.**B1**.

The rest of Europe has a medium (10%-50%) or low share (0–10%) of district heating systems because of the incumbency of individual natural gas boilers. European countries with a medium share of district heating systems, scattered around Central Europe, Eastern Europe, and Baltic, and Nordic regions, often operate on fossils with some exceptions of biomass and waste (Vazquez and Victoria, 2020). Notably, Austria and Finland are the only countries that increased their district heating capacity where a greater share of biofuels was utilized compared to other countries with a medium share of district heating systems (Vazquez and Victoria, 2020). There are multiple factors which lead to the heat capacity reduction in these countries, including but not limited to barriers against retrofitting the heat network (incremental optimization in Fig. 10.**B1**), reduction in heat demand due to population decline, and necessary investment to connect more buildings (economies of scale and scope in Fig. 7.**R2)**. For example, in Hungary and Poland, the regulation of heat prices presents a barrier to retrofitting the heat network; district heating companies are having trouble securing finances because their annual profit cannot exceed a certain threshold for affordable energy prices, which implies both the split-incentive effect in Fig. 9 as well as incremental optimization in Fig. 10.**B1**.

Countries with a small share of district heating systems, across Central and Southern Europe, mostly use individual boilers with mainly natural gas along with oil and other fossil products. For these countries, the established natural gas networks make the case for switching to district heating systems less cost-effective and deem individual natural gas boilers more feasible. To illustrate, the UK and the Netherlands both have natural gas reserves in their economic regions, and thus both invested heavily in natural gas grids. In Southern Europe, the warmer climate reduces the incentives for district heating systems because their utilization rate of the installed capacity would be lower than the colder regions such as Nordic or Baltic countries. In southern regions, heat pumps are an interesting alternative since they can also provide cooling. A small share of district heating systems could imply regulatory and market barriers in the country. For example, the Netherlands[13] is experiencing regulatory problems for stimulating district heating systems as the current monopoly structure creates political friction as shown in Fig. 8.**B2**. Or, Belgium suffers from inconsistencies between regional energy policies and federal energy supply decisions (Vazquez and Victoria, 2020). For countries with a small share of district heating systems, the high capital costs for district heating systems could become a significant barrier when replacing individual natural gas boilers. A necessary number of district heating users is needed to achieve and activate the economies of scale and scope effects. To stimulate district heating in countries with small or medium shares, a well-established regulatory framework is necessary to replace individual boilers and to create incentives for district heating systems by reducing the risks and uncertainty for investors.

In sum, the policymakers need to recognize feedback effects to respond to unintended consequences during district heating transitions such as path-dependencies (e.g. high-level of biomass adoption in Denmark due to the oil crisis), crowd-outs (e.g. barriers for district heating by natural gas in the UK), lock-ins (e.g. coal-coupled heat networks in Romania). Overall, replacing individual natural gas boilers would call for incentivizing district heating systems in Europe, especially in colder countries with low and medium-share of district heating systems to increase their adoption. Our research shows that replacing the individual natural gas boilers might not be enough to mitigate emissions since district heating systems might be required to utilize high-carbon sources, including fossils, to provide affordable or secure energy. Thereby, this could create a lock-in to high-carbon heat networks by crowding out renewable heating systems that could ultimately reduce energy prices in the long term (Gürsan et al., 2024). In contrast, countries with a share of district heating systems would need to retrofit their existing heat networks for renewable heating sources, increase

[13] In the Netherlands, the discussions over co-ownership regulations for district heating systems have intimidated energy companies to continue their investments in heat networks due to uncertainties concerning the future profitability and heat licenses. Although co-ownership in heat networks has been very successful in Scandinavian countries in the past, simply adopting that policy without considering the indirect implications on the policy subsystem can lead to resistance against change as in the Dutch example (de Boer, 2023).

renewable heating capacity in a saturated district heating market, and switch out the biomass and waste CHPs before supply becomes limited. By recognizing feedback effects during transitions, researchers and policymakers could recognize the short and long-term trade-offs for their decisions and potential pathways that could lead to a lock-in to high-carbon heating systems.

5. Discussion

Decarbonizing cities requires understanding which factors influence the co-evolution of energy systems in each socio-technical context (e.g. specific regime, geographical location, path-dependencies, etc.) (Gürsan and de Gooyert, 2021). Feedback understanding can support researchers in identifying the complex and persistent interdependencies that can influence district heating transitions in different contexts (Edmondson et al., 2019). Insights into how district heating systems react to changes in transition policies and vice-versa can shape our understanding of co-evolution (Edmondson et al., 2019). Therefore, recognizing feedback effects and their implications can provide useful insights for policymakers to understand the impact of (unknown) interdependencies and to develop more integrated policies for stimulating energy transitions (Gürsan and de Gooyert, 2021; Gürsan et al., 2024; Rogers et al., 2022). Although recent literature acknowledges (in)consistencies in policies (Edmondson et al., 2019; Unruh, 2000; Cass et al., 2018; Kemp and Rotmans, 2005), policy feedback mechanisms (Edmondson et al., 2019; Béland, 2010; Moynihan and Soss, 2014), and socio-technical interdependencies (Grafius et al., 2020; Rinaldi et al., 2001; Carhart and Rosenberg, 2015), researchers still focus on a limited set of socio-technical factors (e.g. policies, energy systems, markets, geographical scale) to reveal the reasons for complex behaviors during transitions, or simply analyze feedback effects on a conceptual level. This implies that the implications of feedback effects are still investigated within a certain policy silo, where the focus is on a single set of feedback effects under a specific policy domain.

In this research, we opted for a holistic analysis (Gürsan et al., 2023) of feedback effects to advance the debate and knowledge about feedback mechanisms and their implications for transition governance. We aimed to achieve this goal by investigating a geographically and contextually broad continent, Europe, which is also cohesive in terms of policy-making due to the binding EU-wide agreements (Kranzl et al., 2022). The models discussed above show that various feedback effects are interconnected. This research contributes to the transition governance literature by explaining the mechanisms behind how each transition policy influences not just its policy subsystem, but also through feedback loops also a wider range of policy subsystems (Edmondson et al., 2019). These accumulating influences often (trans)form resilient structures across the socio-technical system (de Gooyert et al., 2016a), where energy systems co-evolve to achieve (or fail) net-zero targets alongside the institutions that govern them (Unruh, 2000, 2002). To illustrate, although policymakers aim to decarbonize district heating systems by enforcing network operators to mitigate greenhouse gas emissions of their energy operations, the regulatory barriers against third-party access, unbundling, and deregulation of the district heating markets could still delay achieving of net-zero heat networks (Lavrijssen and Vitéz, 2021). The monopolistic ownership structure of district heating networks could reinforce barriers to deregulation and unbundling of district heating services (Lavrijssen and Vitéz, 2021). As a result, these overlooked dynamics between interconnected feedback effects could lead to higher energy prices due to a lack of competition in the heat market as well as a lack of readiness for low-temperature heating, unless integrated policy measures are developed (Gürsan and de Gooyert, 2021).

In practice, overarching policy targets, such as "sustainable and net-zero cities", are very intangible, and need to be translated into more concrete, quantifiable, and operational policy sub-goals within different policy fields which operate as silos (Veeneman et al., 2009). During this translation, experts and stakeholders focus on their own agenda in alignment with their own responsibility domain, thus overlooking the goals and interests of stakeholders in different silos (Veeneman et al., 2009). This friction between silos could lead to inconsistent sub-goals that ultimately work against each other as actors aim to influence the socio-technical system to achieve different sub-goals (Ma et al., 2021; Rogge and Reichardt, 2016). As a result, policies are developed within a policy silo without considering policies in other silos (Liu et al., 2019b). To illustrate, the affordability of energy services is considered under the policy domain "energy price", while our results also illustrate that the price of energy services has significant implications for the heat demand of the network due to the legitimization of fossil heating for energy security. In consequence, overlooking feedback effects might result in policies that support sub-goals, interests, and activities within one silo but might be inconsistent with policies in other silos (Rogge and Reichardt, 2016).

For example, the split-incentive effect shown in Fig. 9 can explain inconsistencies in policy-making. Understandably, energy companies aim to maximize the profitability of their services (Lavrijssen and Vitéz, 2021). This is typically caused by high levels of investments and long recouping times in infrastructure projects (Bitsch et al., 2012; Galonske et al., 2004). However, this type of narrow subsystem focus disregards the possibility that competition in the heat market could reduce the energy prices for consumers, increase economies of scale & scope, increase the number of district heating users, and thus increase the profitability of energy companies back again. If overlooked, the same mechanism can work in the opposite direction: preventing third-party access and competition could increase the energy prices for consumers, decrease economies of scale & scope, and thus reduce the profitability of energy companies as a result of diminishing district heating users (Hawkey and Webb, 2014; Lavrijssen and Vitéz, 2021). Solving a complex problem, such as the split-incentive effect, calls for a concrete transition roadmap for energy efficiency measures and renewable heating capacity which consists of desired heating capacity for renewables and individual boilers at different time frames to enforce necessary renewable heating investments (Gürsan and de Gooyert, 2021), regulations for separating district heating prices with the energy demand to stimulate energy efficiency (Li et al., 2015), and incentives for citizens to stimulate insulation in the urban environment (Mulder et al., 2021).

Notably, power and natural gas markets have gradually been deregulated and unbundled over the years as opposed to district heating markets. Third parties and intermediaries were allowed access to power and gas markets, which reinforced the benefits of the competition (Lavrijssen and Vitéz, 2021). In contrast, district heating markets are still highly regulated markets in Europe since energy companies need to acquire heat licenses to deploy and operate heat networks and to sell heat in that specific urban region (Lavrijssen and Vitéz, 2021). Therefore, the current monopolistic ownership structure of district heating networks could create barriers to the deregulation and unbundling of district heating services, which might be needed to instigate competition in the heat market and the integration of renewable sources via third parties (Lavrijssen and Vitéz, 2021). Overlooking feedbacks could blindside policymakers and actors (de Gooyert et al., 2016b) by making them consider and act on short-term gains by adopting an isolated policy subsystem perspective which might eventually constrain long-term benefits.

Overall, European governments need to navigate through making these necessary regulatory and market changes for district heating systems while maintaining the trust of licensed network operators for their continued investments in these systems. That being said, the limited innovation potential from a single licensed network operator might not provide sufficient renewable energy to satisfy the urban heat demand in an expanding heat network, and thus justify further investments in efficient yet high-carbon cogeneration systems (Hawkey and Webb, 2014; Lavrijssen and Vitéz, 2021). Overinvestment in high-temperature heating systems could change the understanding of "decarbonizing the network" from *integrating renewables* to *capturing carbon (*Janipour et al., 2021*)*. Ultimately, this could lead to lock-in to third-generation heat networks coupled with carbon capture systems unless the necessary changes to the heat markets and district heating services are made.

Modeling feedback effects to govern transitions could provide a useful tool to evaluate and tailor policy instruments and challenge "simple" fixes by policymakers to solve energy transition challenges (Ma et al., 2021), such as "raise taxes for carbon-neutrality", or "use fossils for affordability". Using systems modeling could highlight the feedback mechanisms in policy fields that have not been explored before and be used to recognize the interconnections among different policy fields. Models can be useful tools to understand how policy-making could vary in each context. Specifically, qualitative SD models can embed interdependencies between socio-technical elements, local context, and current policies to recognize unintended system behaviors to interventions and tailor policies accordingly. To illustrate, the split-incentive effect, as shown in Fig. 9, is relevant for European countries that aim to retrofit their existing district heating network to achieve economies of scale (i.e. the Netherlands, UK, Czechia, Romania, etc.) (Vazquez and Victoria, 2020). Proposed policies might be met with resistance, or even fail their aims unless the conflict of interests around energy efficiency is addressed (de Gooyert et al., 2016b) as shown in Fig. 9. To prevent split incentive issues, there is a significant need for a concrete road map or exit strategy for less-efficient buildings (Gürsan and de Gooyert, 2021). Such a roadmap should include, but not be limited to, upper and lower limits of thermal efficient/inefficient buildings for each year, the time allowed for inefficient to insulate (street-by-street, neighborhood-by-neighborhood, municipality-by-municipality, etc.), and funds and incentives and for deploying these thermal efficiency solutions. Without clear roadmaps and deadlines for thermal efficient houses, district heating systems might also be delayed in switching to low-carbon heating systems in especially countries facing district heating retrofit challenges.

Developing such roadmaps calls for answering certain questions: who is responsible for the efficiency upgrades, who are affected by efficiency upgrades, what are the allowed energy efficiency levels at each year, what are the thermal efficiency goals over the years, and what do these goals mean for each of the stakeholders (energy companies, citizens, governments, etc.)? Utilizing modeling techniques, specifically qualitative SD models, could support scholars and policymakers in recognizing these nuanced and long-term influences from the socio-technical system, and tailor policies accordingly as the energy systems evolve.

Overall, designing district heating networks or net-zero systems is a complex and time-consuming task that requires multiple policy adjustments along the way. Transition policies need to dynamically change to deal with unexpected issues which will emerge over the course of different project phases. Therefore, the real challenge during energy transitions is that the governance and institutions developing transition policies need to co-evolve with the results of various policies in various policy domains as well as energy systems along the lines of societal sustainability targets. Building integrated policies requires much more in-depth analysis and discussions, especially on what the overall system goals, conflicts, constraints, and minimum requirements will (have to) be.

5.1. Limitations and future research

Although recognizing feedback in energy transition with systems models could support policymakers in building integrated policies and aligning sub-goals (Gürsan and de Gooyert, 2021; Veeneman et al., 2009), all models ultimately represent a static and aggregated snapshot of the system (Sterman, 2002). First, there is no single socio-technical system, goal, or policy. Rather, there is an array of these components which increases the complexity of analysis (Geels et al., 2017). Second, the system dynamically changes and feedback mechanisms evolve as a result of an accumulation of all actors' actions, which then again (trans) forms actors' actions (Gürsan and de Gooyert, 2021). Choosing different boundary assumptions is bound to bring a range of different research results. Although this research included several European examples to show feedback effects in action, the policy-making for district heating transitions varies across European countries. In consequence, it is virtually impossible to reach a comprehensive list of development trajectories in different European countries.

Our results indicate that no single model can fully encapsulate the complexity and dynamicity of socio-technical transitions. Qualitative SD models are especially powerful when the analysis requires a broad scope and interdisciplinary approaches. A broad scope and integration of multiple disciplines imply that qualitative modeling studies cannot be comprehensive or exhaustive because they lack the depth of disciplinary studies with narrower scopes (Gürsan et al., 2023). Furthermore, SD models are not known to deal with uncertainties which can emerge during transitions (Sterman, 2002). Although dynamic changes in system behavior are hard to conceptualize with accurate models, whether they are quantitative or qualitative, aspiring to do so is still an important endeavor because increasing our knowledge about feedback effects will support policymakers and researchers in reconciling policy silos and recognizing interconnectedness amongst policy subsystems while making decisions (Gürsan et al., 2024).

6. Conclusion

We investigated feedback effects involved in the substitution of individual natural gas boilers with net-zero district heating systems in Europe. We conclude that the co-evolution of transition policies and district heating systems might activate mechanisms that could stagnate net-zero transition efforts unless feedback effects are recognized and subsequently managed throughout transition governance. Revealing interconnected policy subsystems calls for collaboration between national governments, municipalities, energy companies, social organizations, and communities, to make sense of the complexity and to adapt to changing circumstances during energy transitions. Energy transition seldom consists of "simple" fixes as often claimed by popular policymakers or influential actors because each decision impacts the whole system. Utilizing systems models could support transition governance efforts by highlighting and increasing our understanding of the interconnected mechanisms in energy systems, thereby enabling more open discussions in policy-making processes to recognize, adapt, and manage the unexpected dynamicity during transitions.

Ethical Statement

This research has been done in accordance with the Ethical Guidelines stated by Elsevier Publishing.

Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2024.11.067.

Data availability

Available data can be accessed via the Mendeley Data Folder in Appendix A.

Feedbacks in district heating systems and transition policies: a systems analysis of net-zero district heating transitions in Europe (Mendeley Data)

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