Dealing with complexity in energy transitions:

Exploring feedback mechanisms that hinder and help transition governance

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Institute for Management Research

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Table of contents

Chapter 1

Introduction

Transitioning away from fossil fuels in the energy sector

Increasing greenhouse gas emissions [1] and global crises regarding energy security [2,3] increase the urgency for the switch out of fossils to net-zero energy systems. The energy sector, which includes electricity and heat sectors, has been identified as one of the most emitting sectors (31,3% of the global emissions) as shown in **Figure 1a** [4,5]. Moreover, energy security challenges have been key drivers of events for global conflicts and economic crises [2]. The United Nations (UN) has been encouraging policies and action plans to decarbonize the electricity and heat sectors to mitigate the impact of the energy sector on the environment and society [6,7]. Achieving carbon neutrality necessitates urgent action to change how societies produce and consume energy [8]. Alas, the transition in the electricity and heat sectors has been incremental and slow [8]. The current trend in CO_2 concentration in the atmosphere has not improved enough after the Kyoto Protocol and Paris Agreement for net-zero ambitions [7,9], reaching 417.7 parts-per-million (ppm) in 2022 as shown in **Figure 1b** [4,5].

Electricity and heat differ in numerous ways, which makes the transition in each of these sectors uniquely challenging. In the electricity sector, fossil fuels accounted for 61% of produced global energy in 2022 [4]. **Figure 2** depicts the global electricity production by fuel source in the same year: approximately 36% is produced by coal, 22% natural gas, 3% oil, 15% hydroelectric, 9% nuclear, and only 14% renewables [4]. The International Panel on Climate Change (IPCC) highlighted that solar and wind energy technologies have been identified as the globally scalable energy solutions for the electricity sector that can satisfy the growing global electricity demand [10]. Nevertheless, the degree of their relevance depends on the availability of the renewable resource in each region [10]. Furthermore, solar and wind generate electricity intermittently [11]; in other words, the resource availability for sun or wind produces significant fluctuations in power generation. As a result, solar and wind still need the support of other complementary or dispatchable power generation or storage systems [12] to provide uninterrupted power.

The heat sector is also one of the most important components for achieving a net-zero world [13]. According to the IEA, buildings were the largest energy consumers worldwide and will continue to be a reason for increasing energy demand and emissions in the following decades [13] due to the expected population growth in cities [14]. High emissions in the heat sector are mainly caused by the energy intensity of heating in buildings [14]. In 2021, the main energy use by households in the EU was for space and water heating, reaching up to 78.9% of the total energy consumption in the residential sector [15]. Similarly, fossil consumption is considerable in the heat sector. Almost 63% of the total building-related heat demand was satisfied by fossils in 2022 [16,17]. **Figure 3** shows the building-related heat demand by energy source in the EU (along with comparisons across the world): 41,48% by natural gas, 12,36% by oil, 3,67% from coal, 11,76% electricity, 18,89% renewables, 11,71% district heat, 0,13% others (including geothermal, wave, tidal, etc.).

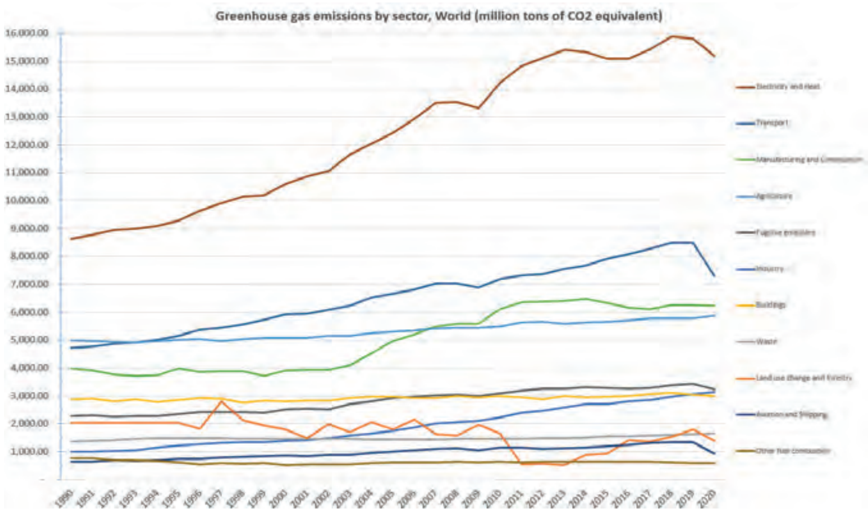

Figure 1a - (Above) Electricity and heat sectors have been the most emitting sectors over the years compared to other sectors [4].

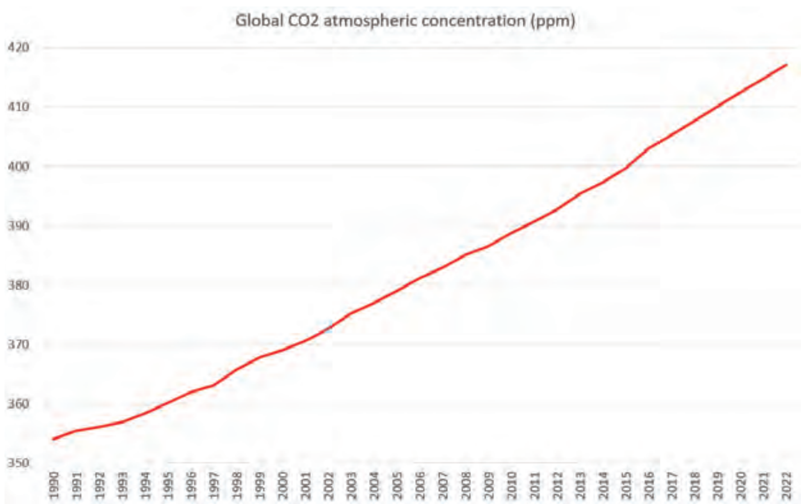

Figure 1b - (Left) GHG emissions have been increasing even though decision-makers have been trying to mitigate the negative impact on climate [5].

Each heating system must be designed locally while considering the intended heating purpose and requirements [6]. To illustrate, large-scale renewable heating technologies (e.g. geothermal, biomass, or solar thermal plants) can be utilized if they are economically feasible and exist near urban areas [18]. Other alternatives, such as heat pumps or solar thermal, are often individual household-level solutions [19]. These systems are notably energy efficient; however, they are typically small-scale (except solar thermal plants or industrial-scale heat pumps [20]), require high insulation levels, and operate at lower temperatures unless complemented with other technologies. Overall, the heat transition necessitates phasing out fossil-fuel-based sources while integrating various, and often smaller-scaled, renewable heating technologies in interconnected urban heat islands [21].

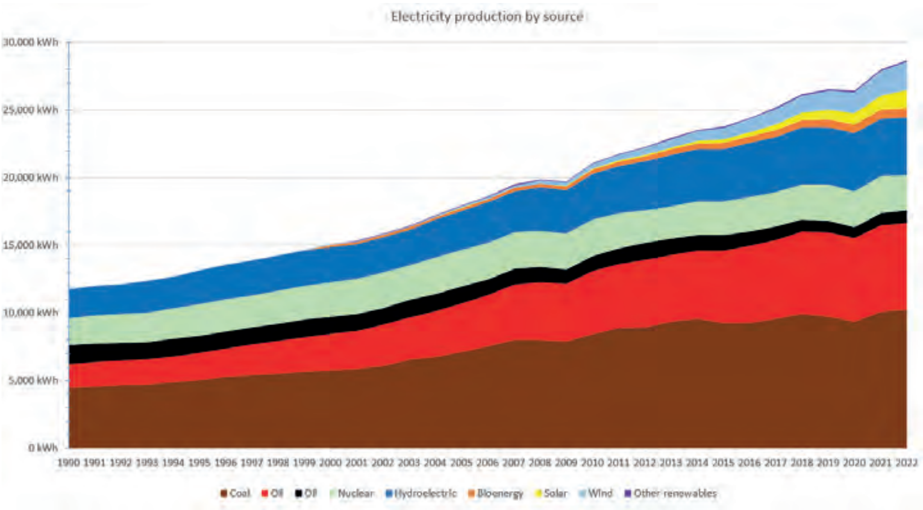

Figure 2 - Electricity production by fuel source between 1990-2022 [4].

In sum, there are no silver-bullet solutions for the electricity and heat sectors. The energy transition in both sectors demands a patchwork of energy solutions to replace fossil fuel consumption and mitigate emissions. However, phasing out fossils and deploying multiple energy systems at the same time is a complex affair because energy systems change and evolve in a path-dependent manner [22,23]. Path dependency in energy transitions can be defined as how energy options available today are shaped by past decisions and policies, historical trajectories, and sequences of events, creating a pathway towards certain energy systems in the future instead of others [24,25], which is also known as a *technological trajectory* [22,23].

In simple terms, investing in a specific energy system over others will have a positive impact on certain energy systems and a negative impact on others in the long term [26]. This interdependent nature and long-term consequences make energy transitions non-linear, transcend system and sector boundaries, and have unintended systemic consequences [18], thereby influencing available pathways for future energy systems [22,23].

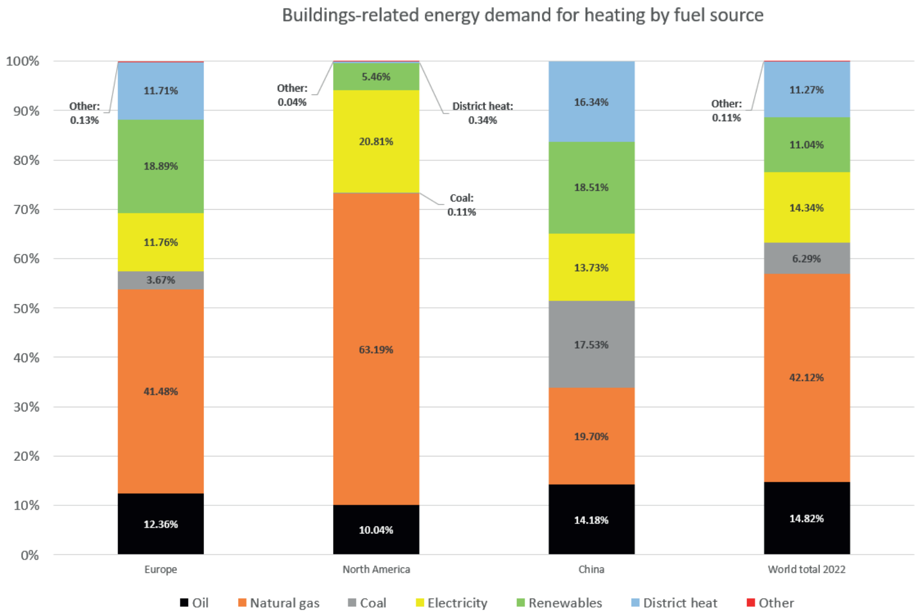

Figure 3 - Building-related heat demand by energy sources in the world and different regions [13].

Interdependency can be defined as the interconnections among system elements or interrelationships between actors that operate together and impact each other in meaningful ways [27]. Energy systems mutually influence each other [28]. For example, the electrification of heating (e.g. a shift from natural gas heating to heat pumps) will also result in new spikes in electricity demand during winter time, with implications for power grids and electricity generation [20,26] This also implies that the energy transition is not simply a technical change, but rather it is the consequence of interconnected social (e.g. urban heat demand, heat markets, local energy policies, etc.) and technical elements (e.g. heating technologies, energy carriers, etc.) in energy systems [29]. These constantly changing interdependencies in the socio-technical system may (re)form feedback effects during energy transitions. Feedback effects are a specific type of interdependency structure where two or more elements mutually depend on each other via interconnected causal relationships [26], leading to a closed loop of cause and effect.

Feedback effects have unintended (supporting or hindering) implications for energy transitions because they result in self-regulating system behaviors, such as exponential change or inertia during energy transitions [18]. To illustrate examples of exponential change, two energy systems may have complementary technical characteristics (i.e. solar energy and electric batteries); thus, developments and innovations in one system can reinforce other systems and vice versa [20]. Or, if one energy system has a distinguishable advantage over another competing energy system, the former energy system can swiftly push out the latter system from the energy markets by utilizing its advantage [20]. For example, district heating systems could not penetrate the UK heat markets due to the incumbency of natural gas [30]. To illustrate examples of inertia, vested interests [31] can create resistance against certain technological trajectories. For instance, affordable energy and sustainable energy targets often work against each other [18]. In another inertia example, biomass is being planned to be used in many energy and chemical sectors, including industrial heat, urban heat, aviation fuel, etc. [32]. Utilizing biomass as an aviation fuel would limit its potential use as an urban heat source [20]. As these examples show, it is essential for scholars and policymakers to recognize and evaluate systemic consequences during energy transitions, which are caused by feedback effects, and to tailor policies to address unexpected outcomes during energy transitions.

In their latest future agenda for sustainability transitions research, Köhler et al. [31] highlight the necessity for conducting more research on feedback effects [33] to recognize and address these unexpected systemic consequences for achieving net-zero targets [34]. Scholars [26,31,35] suggest the development of systems approaches and analyzing beyond only a handful of energy systems, a single characteristic in the energy transition (innovation, policy, markets, etc.), a single governance level (local, national, global), a single sector (electricity, heat, mobility, etc.), single policy instrument (e.g. tax on natural gas, insulation for urban areas, etc.), or single technology (solar power, natural gas heating, district heat, etc.) [28,34]. Moreover, interdependencies in energy systems cannot be understood in simple polarities (e.g. complementary vs. competing) due to the feedback effects [20]. Exploring feedback effects in energy systems requires a holistic approach that goes back and forth between global and local dynamics across multiple sectors [35,36] as well as immediate and long-term consequences [26,31] for multiple cooperating and competing energy technologies and transition policies [37,38].

Advancing the understanding of feedback effects in energy transitions will aid scholars and policymakers in assessing dynamic interdependencies and feedback effects in energy) systems [39], recognizing contemporary and structural couplings in energy systems [40], and exploring systemic patterns responsible for future energy pathways and their implications for the energy transition as a whole [36,41,42]. In doing so, scholars and policymakers can strengthen the scope of cross-sectoral value generation in energy transitions [43], avoid unwanted consequences during transitions [26], and work beyond silos and disciplines [18]. This thesis aims to aid scholars and policymakers in recognizing, understanding, assessing, and explaining feedback effects that can help or hinder energy transitions. To achieve that, this research explores and discusses feedback effects in the energy transitions with a holistic lens that covers multiple energy technologies in different sectors (electricity and heat) and governance levels (local, national, global) [35] over various time horizons [20] through synthesizing knowledge from System dynamics (SD) modeling approaches, transition research, and engineering disciplines [44].

Feedback effects in energy systems and transition governance

Energy systems are considered as socio-technical systems because their social aspects cannot be separated from their technical aspects [45]. This indicates that an energy transition occurs as a consequence of interactions between society and technology. Experts and society form institutions that recognize, regulate, and govern societal interests [46]. Institutional organizations (national and regional governments, municipalities, etc.) develop policies, engage in lobbying activities, build coalitions, and shape norms and culture, which produces energy systems [47]. Depending on the analysis, energy systems or technologies can be considered as socio-technical by themselves or as significant components of other systems (e.g. district heating system as a part of urban heating system as a part of urban services, and so on), which are governed via complex structures operating at different governance levels (international, national, municipal, etc.) [53]. According to Unruh [47,48], institutions and energy systems together form a resilient structure, known as the techno-institutional complex, and co-evolve to address constantly evolving needs in society [29,49]. This co-evolution also implies that energy systems and transition policies are interdependent which can ultimately (re)form feedback effects.

According to the transition governance literature, institutional rules and guidelines provided by society specify the roles and responsibilities of policymakers [47]. Actors responsible for policies and decisions are tasked with protecting the stability of societal activities by identifying and addressing societal needs and services (e.g. energy demand) [26]. Typically, policies are developed in policy environments to accomplish a set of policy goals for society (e.g. affordability of energy prices, urban mitigation, etc.) [50]. Each policy-maker is responsible for their respective policy domains, subsystems, and targets [54] which can be discussed as sub-sets of more complex overarching sustainability targets (e.g. net-zero energy systems) [50]. Policy subsystems can be conceptualized as sets of dynamic relationships between policymakers and interest groups in socio-technical systems [54]. 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 [51]. This implies that there could be a myriad of interdependencies and feedback effects in energy systems and transition policies [51]. To give an example, policy choices (in a policy subsystem) can affect the technological trajectory of energy systems through incentives, regulations, or resource allocation that promote the development of particular energy technologies [52]. In contrast, changes in energy systems (e.g. innovation, user preferences) can lead to reform or change in policy subsystems and their respective policy choices [20]. On the whole, each policy affects not just its subsystem but also the entire socio-technical system through a structure of feedback mechanisms [18]. These characteristics also imply that exploring feedback effects requires an understanding of 'system of (sub)systems', which would necessitate going back and forth between global, regional, and local (sub)systems across different energy (sub)systems with a holistic lens. Unless recognized, feedback effects can accelerate or hinder energy transitions through these indirect, long-term, and unexpected systemic consequences [26].

Scholars and experts suggest that developing a roadmap is necessary for energy transitions [16,19,26]. For this thesis, a transition roadmap can be conceptualized as the strategic plan, which is developed as a consequence of policy-making practices, that defines the desired goal and includes major milestones needed to achieve the intended transition. To create a roadmap toward net-zero energy systems, policymakers need to be aware of indirect and long-term consequences of their decisions that might not be so apparent during the decision-making process. Alas, policymakers may fail to recognize feedback effects due to the indirect relationships among different policy domains because the causes or consequences of feedback effects often fall under the responsibility of other policy silos [18]. This thesis aims to advance the academic debate by exploring and elaborating on the systemic consequences of energy transition policies (e.g., path-dependency), often caused by feedback effects working together or against each other [26]. This research explores and discusses feedback effects in energy transitions to aid scholars and policymakers in recognizing and assessing the systemic implications of transition policies in different contexts. To advance the knowledge of feedback effects, this thesis utilizes and proposes SD models to explore and discuss the complexity caused by feedback effects during energy transitions and their governance.

System dynamics to explore feedback effects

Scholars suggest adopting systems approaches to develop a more holistic understanding of energy transitions [36,44,53]. System dynamics is a scientific tradition that puts feedback effects at its focal point to recognize interconnectivity and long-term consequences in complex systems [33]. SD models can investigate and explain cause-and-effect relationships in a system's structure [33]. The main premise is that these cause-and-effect relationships are rarely unidirectional but rather also form feedback effects [54]. SD investigates and elucidates such feedback effects to recognize the complexity behind the system's behavior and potential consequences [26]. SD models highlight feedback mechanisms that often transcend the boundaries of different disciplines, sectors, and systems [26]. This is especially useful for energy transitions because transitions require the collaboration of policymakers, actors, and interest groups across different domains [31,55]. SD models can synthesize knowledge from different disciplines to recognize feedback mechanisms that often occur across the boundaries of distinct domains [18].

Nonetheless, modeling energy transitions is a difficult undertaking [20]. To clarify, stakeholders and experts perceive energy systems and their transitions differently. This difference is caused by the variety of beliefs, goals, and assumptions of each stakeholder about the role, capabilities, and transition of energy systems. Each stakeholder perceives and act in the world in accordance with their beliefs, goals, and assumptions, otherwise known as mental models, of how the world operates [54,56]. Thus, each stakeholder tries to bring about their ideal energy system according to their interpretation of the energy transition. This also indicates that experts and policy-makers are limited in their ability to recognize feedback effects because they are constrained by their own expertise and responsibility domains [18]. Furthermore, the interrelationships in energy technologies [37,38] or transition policies [57] are not a dichotomy. In other words, there are more complex relationships than simple "complementary" or "competing" interactions between energy technologies or transition policies. Instead, there are certain tipping points or system thresholds [31], and when passed, feedback effects can activate mechanisms that support certain energy systems or transition policies while hindering others during transitions [26], and thereby the energy transition as a whole.

Often, transition decisions and policies lead to heated debates about their expected and intended effects because the observed and conceptualized causal relations could vary depending on the mental models of each stakeholder [26]. Notably, SD models can synthesize varying views from different experts to contrast these views, develop a (more) holistic understanding of the system, and offer novel insights for stimulating energy transitions [26]. At this stage, it is important to note that achieving an exhaustive or definitive map of interdependencies or feedback effects is virtually impossible [20] due to the differences in perceptions of causal relations in energy transitions. Nevertheless, scholars and policymakers can benefit from such modeling efforts [55] because investigating this complexity will aid them in understanding patterns through which energy systems and transition policies might interact as well as their implications on the energy transitions as a whole [41].

Notably, qualitative SD models explore and describe the complexity in transitions by collecting and connecting inputs from various primary and secondary data sources [58]. Qualitative SD models can produce conceptualizations of complex problems and offer novel insights on energy transitions by using these pieces of this "interdependency" puzzle articulated by different reports, documents, experts, decision-makers, and researchers [58,59]. Thereby, qualitative SD models can be used to visualize, recognize, and explain feedback effects in energy transitions to identify influential systemic mechanisms and consequences for transition policy-making [26]. Given the complex interconnected nature of energy transitions, qualitative SD models in this research were utilized to advance the debate on how feedback effects impact energy transitions and transition governance. More information on qualitative SD model notations follows in the next subsection.

System dynamics notation

This subsection introduces systems modeling approach, namely Systems Dynamics, that this thesis utilized in third [26], fourth [18], and fifth [60] articles. SD is a systems approach for modeling and analyzing the behavior of complex systems over time [54]. SD models can facilitate new insights into how different system elements influence each other and what mechanisms drive the behavior of the (socio-technical) system at large. SD models conjoin system elements in causal links, which form the foundation for revealing feedback structures [33]. A causal link, or an arrow, connects two system variables to show the nature of the relationship between the two elements [33]. There are two types of causal relationships in SD models. A "**+**" sign on a causal arrow indicates that the interconnected variables change in the same direction. If the cause element increases, then the consequential element also increases. The other direction also applies: if the cause element decreases, then the consequential element also decreases. In contrast, a "**-**" sign denotes that the interconnected variables change in the opposite direction. In other words, if the cause element increases, then the consequential system element will decrease. Or, if the cause element decreases, then the consequential system element will increase. A delay sign on a causal arrow "**||**" means that the causal effect does not happen instantaneously but with a temporal delay [26].

By connecting influential system elements in causal links, SD models can depict feedback structures that are responsible for behavior of a system [33]. These mechanisms are represented by closed loops of causal arrows in SD models. There are two types of feedback mechanisms: reinforcing and balancing [33]. Reinforcing loops are shown with a **R** letter and balancing loops are shown with a **B** letter. In reinforcing feedback mechanisms, a system element reinforces itself through a closed causal chain [18]. Therefore, these types of feedback lead to exponential behavior unless they are balanced by other system elements [18,26]. In balancing feedback mechanisms, a system element restricts its further change by balancing the initial force on the system element through a closed causal chain [18]. Balancing feedback mechanisms results in a stabilizing or limiting effect on the system since they pursue an equilibrium [18,26]. 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 [18,26].

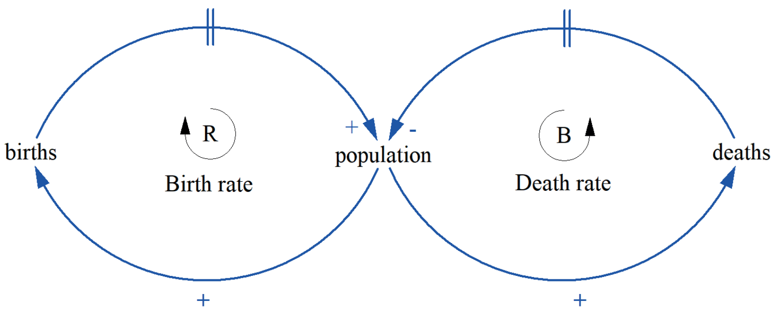

Figure 4 - A causal loop diagram for reinforcing and balancing feedbacks [33].

Figure 4 shows an example of both reinforcing and balancing feedback loops in a SD model. On the left side, both population and births move in the same direction, resulting in a reinforcing loop. In this reinforcing loop, as the population increases, births also increase. Subsequently, an increase in births also increases the population. This indicates that the population will continue to increase exponentially if this mechanism is isolated. In this example, the birth rate is balanced by the death rate. On the right side, deaths do not move in the same direction as the population, resulting in a balancing feedback mechanism. An increase in population will also increase the number of deaths. When deaths increase, this reduces the population. Overall, interconnected variables in the system structure form feedback mechanisms that drive the system behavior. Feedback mechanisms, as shown in this example model, operate in similar or opposite directions in tandem. The resulting behavior of the system (the value for population) occurs as a result of these simultaneous feedback mechanisms (births and deaths).

Depending on the available data and research aims, SD models can be based on quantitative or qualitative relationships [58,61]. When quantitative data is available, quantitative models are used for simulation experiments where the system behavior can be tested under various assumptions or scenarios. This increases the richness of insights on how feedback mechanisms influence the system behavior [58]. However, the complexity and uncertainties in the topic of energy transitions are of such a high degree that any simulation might give a false sense of security for its claims. In contrast, qualitative SD models can combine narratives and claims from different disciplines to describe complex concepts and explore a myriad of interdependencies from different authors and experts [20]. This is especially necessary for energy transitions since the data required for understanding interdependencies are often rich in text yet seldom quantified due to the contemporary nature of the topic [61]. While exploring complex and contemporary issues, qualitative models can alleviate the potential boundary challenges by including interdisciplinary knowledge from various primary and secondary data sources. On the other hand, qualitative models cannot make as accurate claims as quantitative models [58] because they lack simulation experiments. Nevertheless, qualitative SD models can help to integrate a rich set of interdisciplinary information into a coherent framework and generate insights that can explore the complexity of energy transition challenges with a holistic lens, thereby improving coherent and consistent communication for complex topics during energy transitions [26,62]. Due to the fit with the research aims, this thesis utilizes qualitative models to explore and discuss feedback mechanisms in energy transitions and their governance.

Research aims

This dissertation heeds the call for research on feedback effects, employs a systems approach [35,53], and goes back and forth [36] between socio-technical elements [35] and different levels of governance [31] over a long time horizon [26]. To interpret cross-cutting influences across energy systems [18,26], this thesis conducts four studies which span across different energy technologies (30 different energy technologies and infrastructures), different energy sectors (electricity and heat), different geographical scope of regions (the Netherlands, the world, Rotterdam, Europe), and their respective socio-technical elements. This thesis collects qualitative data from academic literature [63], interviews [64], participative modeling workshops [65], technical and project reports, and policy documents [63], and then it embeds the investigated phenomena in qualitative SD models to explore and discuss the implications of feedback effects in energy transitions [66].

This thesis contributes to the energy transition efforts by advancing the understanding of and supporting the recognition of feedback effects in energy transitions and promoting cross-disciplinary communication between policymakers, experts, and researchers to enable decision making for systems which are by feedback effects. Each chapter explores influential feedback effects in different contexts, discusses how feedback effects stimulate or restrict the pace of energy transitions in that context, and analyzes the role and characteristics of feedback effects in energy systems and transition governance. The final chapter brings together findings from each study to answer how feedback effects can affect energy transitions and their governance. The research questions answered in this thesis are shown below.

Main question:
What feedback effects affect energy transitions and their governance?

Chapter 2: What types of socio-technical interdependencies amongst infrastructure systems influence urban climate mitigation efforts?

The second chapter explores socio-technical interdependencies to build the conceptual foundation for this thesis [20]. It conceptualizes different types of interdependencies between urban energy infrastructures in Dutch cities. The reason for focusing on cities in the first study was that cities are still the main hub where the majority of the global population is expected to live, use energy, and emit greenhouse gases [14,67]. Furthermore, cities have a high density of energy infrastructures and require energy services. These factors make it more than likely to encounter and analyze a myriad of socio-technical interdependencies. The results from the second chapter offer an interdisciplinary framework to explore, understand, and discuss interdependencies and their implications for energy transitions [34,68].

Chapter 3: What are the effects of using natural gas as a transition fuel in terms of helping or hindering the energy transition?

The third chapter [26] introduces qualitative SD models as a way to explore and discuss feedback effects in energy transitions. It investigates the role of natural gas as a transition fuel in the electricity sector on a global scale to explain how interdependencies influence the switch from coal generation to intermittent solar and wind energy [69,70]. This topic was chosen because using natural gas as a transition fuel led to heated debates between scientists and decision-makers [71]. This chapter advances the ongoing debate on using natural gas as a transition fuel by exposing how the positive and negative effects of energy transitions are interdependent via feedback mechanisms. The resulting models indicate that positive immediate and local benefits of natural gas also lead to unwanted long-term and global effects which can work against energy transitions and net-zero targets.

Chapter 4: What are the socio-technical interdependencies that can help or hinder carbon-neutral heating in Rotterdam?

The fourth chapter investigates the role of district heating systems in Rotterdam to explore how feedback effects in the urban heat sector influence the pace of the energy transition [18]. District heating systems are considered a viable option to replace natural gas in high-density cities for reducing urban emissions such as Rotterdam [6,32]. This study focuses on an urban case because many researchers [72–74] highlighted that energy transitions are notably influenced by their local context. This is especially true when it comes to urban transitions because of the density and proximity of energy services and infrastructures [18]. The resulting models indicate that current policies might lead to a rivalry between energy security and energy efficiency, which are both crucial goals in transition governance. The results from this chapter indicate that each transition project requires a tailor-made solution that can recognize socio-technical interdependencies and potential feedback effects for that local context.

Chapter 5: What are implications of feedback mechanisms on energy systems and transition policies that seek to substitute natural gas heating with district heating systems for carbon-neutral European cities?

The fifth chapter [60] explores district heating transitions by broadening the geographical scale and time frame as the previous chapters suggest [18,20,26]. This topic was chosen for this research because the third chapter revealed that district heating systems are one of the most complex heating systems due to their socio-technical interdependencies. This follows from the fact that they are larger-scale heating systems which can interconnect a wide range of customers, heat providers, and heating technologies. This chapter maps out how feedback mechanisms are (re)formed in and between energy systems and transition policies throughout the transition governance process [51] by highlighting the mechanisms that bridge the energy policies, disciplinary actors, and consequential change in energy technologies.

Chapter 6: Conclusion The sixth chapter closes this thesis with a general discussion and conclusion. This final chapter includes a summary of chapters, contributions to the academic literature, interpretation, and synthesis of findings, suggestions for future research, implications for transition governance, limitations, and concluding remarks.

Figure 5 shows a network map of how the articles in this thesis are connected and **Table 1** describes the scope and dimensions of each study. Each chapter focuses on a different aspect of interdependencies and feedbacks in energy transitions. The commonalities and differences in each article, which are described in **Figure 5** and **Table 1**, explain to the reader how different studies together form a cohesive narrative of feedback mechanisms in energy systems and transition policies to answer the main research question.

Table 1 - Dimensions of the articles included in this thesis

No	Article Name	Scope	Location	Energy Sector
1	Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent insights from the Netherlands	National	the Netherlands	Electricity, Heat, Mobility
2	The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition?	Global	-	Electricity
3	District heating with complexity: Anticipating unintended consequences in the transition towards a climate-neutral city in the Netherlands	City	Rotterdam	Heat
4	Feedbacks in energy transition governance: a systems analysis of European district heating policies	Continental /Global	Europe	Heat

Contrast	Relevance and Content	Included Energy Technologies
Conceptual research on recognizing socio-technical interdependencies	I introduced the existence and mechanisms of interdependencies in (socio-technical) energy systems which worked as an interdisciplinary framework and boundary for future studies.	Solar - Power, Wind, Biomass - Power, Natural gas - Power, Smart Grids, Electric Batteries, Hydrogen Electrolysis, Hydrogen Storage, Biogas Injection - Heat, Hydrogen Injection - Heat, Heat Pump - Individual, Heat Pump - Central, Biomass - Heat, Aquathermal, Geothermal, Residual Heat, District Heating, Solar - Heat, Heat Storage, Biofuel - Mobility, Hydrogen - Mobility, Electric Car Batteries, Fossil Fuel - Mobility
Modeling study on in the electricity sector to highlight global systemic effects	I zoom out and demonstrate that unwanted system behaviors (indirect and long-term consequences) are often caused as a result of feedback effects by investigating the use of natural gas as a transition fuel in the global power sector.	Natural gas, Coal, Solar - Power, Wind, Carbon Capture Storage and Utilization
Modeling study in the heat sector to highlight systemic effects from local contexts	I zoomed in on an urban district heating transition in Rotterdam and utilized Group model building approach to explore and explain how feedbacks are influenced by their local contexts.	Natural gas, District Heating, Geothermal, Aquathermal, Combined Heat and Power, Residual heat, Waste-to-Energy, Carbon Capture Storage and Utilization
Modeling study in the heat sector to synthesize global/local effects for district heating systems	I zoom out again on Europe and investigate district heating transitions at a longer-time period across different regions to conceptualize the interdependencies and feedbacks between energy systems and transition policies.	Natural gas, Coal, Oil, Combined Heat and Power, Biomass, Waste-to-Energy, Geothermal, Residual

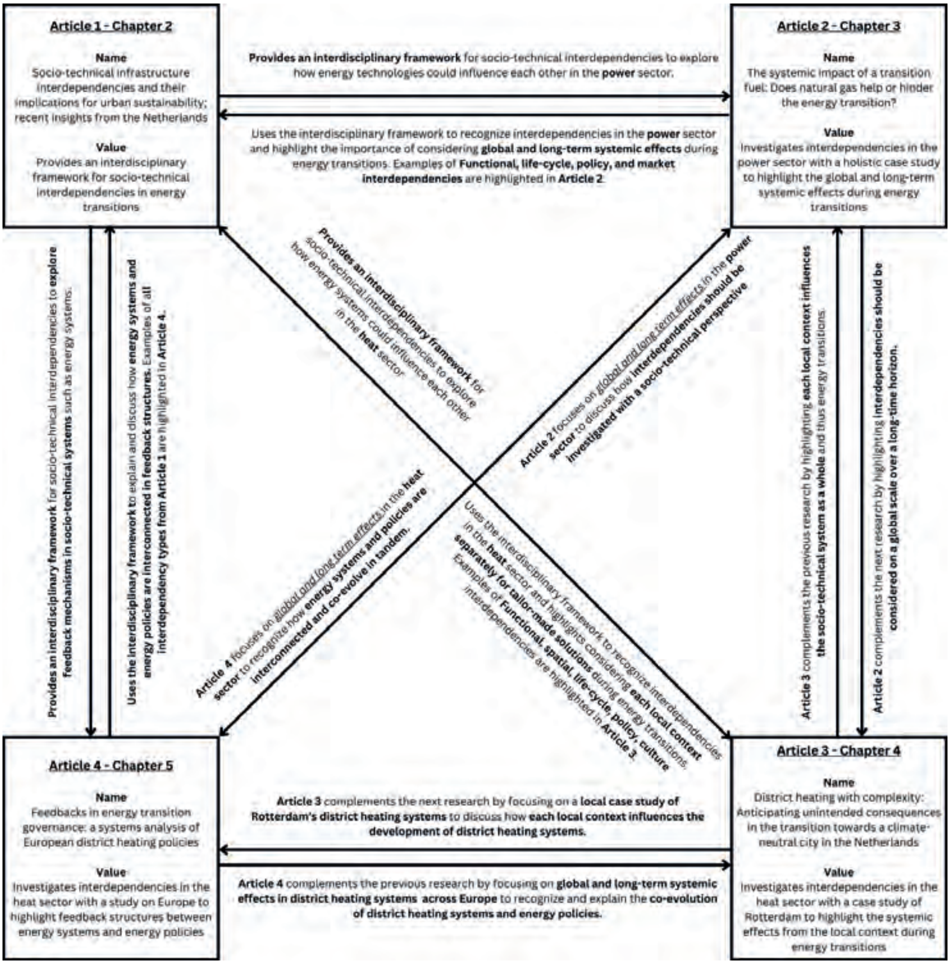

Figure 5 - Network map of articles in this thesis. The differences between articles are shown in bold font.

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Chapter 2

Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent insights from the Netherlands

This research has been kicked-off for the INSpECT project in 2020 under the supervision of Prof. Dr. Etiënne Rouwette, Dr. Vincent de Gooyert, and Dr. Mark de Bruijne. The work-in-progress research article was presented at the NEST (The Network for Early Career Researchers in Sustainability Transitions) conference in Sofia - Bulgaria in 2021. The article was later published at the Cities Journal in 2023 and was co-authored by Dr. Vincent de Gooyert, Dr. Mark de Bruijne, and Prof. Dr. Etiënne Rouwette. During the publication process, Prof. Dr. Chris Rogers from University of Birmingham commented that the research done in this work is seminal for energy transitions and highlighted it as a necessary read for scholars who works with interdependent infrastructures.

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Abstract

Cities are increasingly recognized as potential motors of sustainability transitions. These transitions build on existing as well as new infrastructures, and these infrastructures mutually influence each other in many ways, a phenomenon known as infrastructure interdependencies. These infrastructure interdependencies have significant implications for both enabling or restricting urban sustainability transitions but their implications remain understudied. We elaborate the role of interdependent infrastructure systems from a socio-technical perspective and explore recent examples of how socio-technical interdependencies in infrastructure systems influence urban sustainability efforts. We analyze infrastructure interdependencies in the Netherlands which is relevant because of its high urbanization rate, dense urban areas, and innovative developments. We distinguish seven socio-technical infrastructure interdependency types that can influence urban sustainability transitions: functional, evolutionary, spatial, life-cycle, policy/procedural, market, and culture/norm interdependencies. We identify and discuss contrasting multi-mode relationships of each interdependency example. Our results offer an interdisciplinary framework and examples of potential influential infrastructure interdependencies to explore, understand, and discuss the implications of infrastructure interdependencies for urban sustainability transitions.

Keywords
Urban climate mitigation; Infrastructure systems; Infrastructure interdependencies; socio-technical systems; multi-level perspective; multi-mode interactions

Introduction

Today, cities accommodate approximately 55% of the global population whereas they account for more than 60% of global energy use and 70% of emissions [1,2]. The UN expects that the urban population will reach 68% by 2050 [3]. Since cities are the main hub where the majority of the global population is expected to live, use energy, and emit greenhouse gases, any long-term climate plan has to take a fundamental reshaping of current-day cities into account [4].

Infrastructure interdependencies have significant implications for both enabling or restricting the urban climate mitigation but remain understudied [5]. Infrastructure systems mutually influence each other. To illustrate, a shift from the use of natural gas to district heating will also result in a shift from natural gas to induction cooking. This comes with a new spike in electricity demand around dinner time, with implications for the electricity grid. Such interdependencies can (re)form the interconnections between system elements, influencing how resilient or flexible the transitioning system is to realignments and change. An increased understanding of infrastructure interdependencies supports urban mitigation efforts by clarifying how social and technical dimensions of infrastructure systems are interconnected and how these interconnections impact the system as a whole [6]. Recognizing infrastructure interdependencies helps identifying patterns that can facilitate change in urban infrastructure systems, avoiding unexpected consequences, and overcoming system lock-ins [5].

Although infrastructure interdependencies were highlighted previously [6], earlier works often focused on only a handful of infrastructure systems, a single aspect of infrastructure systems (e.g. technological, economic), or single infrastructure sectors (e.g. electricity, heating) which limits the investigation of such interdependencies [5]. This is understandable because the topic is complex due to the high interconnectivity between system elements. This is also reinforced by the fact that infrastructure interdependencies can easily cross sector or system boundaries [4]. Finding ways to structure the interconnected mechanisms between infrastructure systems can increase the understanding of urban sustainability transitions and support urban decision-makers and researchers in working beyond silos or disciplines. Mapping infrastructure interdependencies can strengthen and broaden the scope of cross-sectoral value generation in cities.

The objective of this study is to contribute to sustainability transitions by supporting the identification and recognition of infrastructure interdependencies in the urban climate-mitigation context and thus promoting communication across disciplines which can help addressing challenges and seize opportunities born out of the interdependent nature of urban infrastructures. We analyze the role and characteristics of infrastructure systems from a socio-technical perspective, bridge earlier interdependency and systems frameworks to recognize infrastructure interdependencies, explore up-to-date examples of interdependencies in Dutch cities, and finally discuss how these examples of socio-technical interdependencies can influence urban climate mitigation efforts. We investigate the instances and examples in the Netherlands because the country has high urbanization rates, a high density of infrastructure services, and adopts innovative technologies. These factors make it likely to encounter a myriad of relevant infrastructure interdependencies in the Dutch context. The research question is: what types of socio-technical interdependencies amongst infrastructure systems influence urban climate mitigation efforts?

Theoretical background

Infrastructures as socio-technical systems

Infrastructure systems refer to socio-technical systems [7] that produce, process, and distribute specialized services, materials, and assets [5] and thus support the well-being of citizens and proper functioning of cities. An important societal function of infrastructures is supporting urban services such as the provision of energy, water, heating, mobility, and sanitation. Through these services, infrastructure systems support societal needs [8]. To illustrate, public health is supported by water and sanitation services or comfort at homes by heating services.

Over time, service users and experts form institutions to recognize, regulate, and govern collective interests [9]. Societal institutions shape infrastructure systems by policies, lobbying, building coalitions, and forming the foundations for social norms, customs, and culture [10]. Infrastructure systems shape institutions to recognize and satisfy societal needs through their functions [11]. Therefore, institutions and infrastructure systems co-evolve over time by addressing and shaping societal needs [12]. Looking from a transition governance perspective, the multi-level perspective framework (MLP) [7] recognizes interactions between three socio-technical levels through which infrastructure systems evolve: “landscape”, “regime”, “niche”. Niche level innovations and disruptions challenge the status quo and regime and drive towards for optimizations and transitions. The regime level accounts for the societal orientation and coordination of activities that lead the way to the system's stability and change. At the regime level, infrastructure systems are influenced by six socio-technical dimensions, namely technology, policy, science, industry, market, and culture [13]. The landscape level refers to deeper structural characteristics of the external environment (i.e. climate change, wars, etc.) which can exert pressure at the regime level and lead to windows of opportunities. Developments in infrastructure systems can be explained as an outcome of cumulative interactions between these three levels of the socio-technical system [14]. Evidently, transitions in infrastructure systems occur when all the socio-technical dimensions align to form a change in the existing system configuration. Overall, such a framework underpins a better understanding of how infrastructure systems evolve over time.

Current urban infrastructures are part of a system that is responsible for high volumes of greenhouse gas emissions. Incremental changes in infrastructure systems often enable affordability and efficiency of services [15]. That said, the same stability indicates an inertia which might lead to barriers to fundamental changes in societal configurations (i.e. urban mitigation) [5]. Incremental changes might not suffice to achieve climate goals, whereas fundamental changes can be resisted by the existing socio-technical configuration [16]. Thus, a successful urban mitigation requires an understanding of how infrastructure systems are reconfigured.

Reconfiguration of infrastructure systems

Infrastructure systems evolve path-dependently [6]. In other words, the accumulation of previous decisions, procedures, systems, culture, and knowledge influence the decision-making environment of today and feasible pathways of tomorrow. Path-dependent evolutions of an infrastructure system give rise to *technological trajectories* [15]. A technological trajectory can be defined as "the direction [in] which the technological paradigm advances" [14]. Trajectories are influenced by interactions between socio-technical dimensions such as technological evolutions, policies and legislation, market and user preferences [17]. The co-evolution of infrastructure systems is not deterministic; in fact, these systems are viewed varyingly by different stakeholders, each catering to their own expertise, beliefs, goals, and judgements, in other words, their mental models. Each person has a mental model, an image or abstraction of how the world works that consists of a wide range from intuitive assumptions to real-life observations [18]. Stakeholders try to materialize changes on infrastructure systems that they believe are beneficial according to their mental models [19]. This also implies that actors' abilities to recognize infrastructure interdependencies over a range of sectors and systems are limited to their own perceptions, biases, and expertise.

Infrastructure systems often favor incremental reconfigurations and optimizations due to the high investment costs and long life-cycles of infrastructures. Previous studies have focused on how to accelerate transitions in urban infrastructure systems [6] through exploring the influential interactions between infrastructure systems [19,20] because understanding infrastructure interdependencies could reveal the role of infrastructure systems as enablers and barriers for transitions. To illustrate, institutions create the disciplinary know-how and knowledge workers [17] which infrastructure systems need to develop incremental and evolutionary advantages [15]. Incremental changes take place to prevent destabilization of infrastructure systems which could negatively affect urban services [6]. Incremental reconfiguration implies that infrastructure services are gradually improved, provided affordably, efficiently, and without interruption [21]. However, incremental reconfiguration may also signal a path-dependent inertia which could lead to lock-ins [17]. Lock-in can be defined as a rigid socio-technical trajectory that favors dominant systems and crowds out other emerging systems [22]. Crowd out can be understood as the obstruction of investments to a desired technology due to the attractiveness of another technology [14]. Rigid trajectories, if under pressure from the landscape, can lead to the dealignment and radical reconfiguration of a system [13] which would hinder the continuity of infrastructure services.

With some exceptions [20], previous studies focused more on the hindering effects of infrastructure interdependencies (i.e. lock-ins, system inertia, etc.); however, utilizing the interdependent nature of infrastructure systems could also lead to transition opportunities such as the spill-over of R&D and investments, windows of opportunities, discovery of new urban functions of infrastructures [23], de-risking decisions and investments by avoiding unexpected consequences, and broadening the scope of cross-sectoral value generation in cities [24]. Therefore, increasing the capability for identifying and making sense of infrastructure interdependencies, their socio-technical interactions, and their implications can support urban decision-makers to make better-informed decisions and avoid systemic traps [6].

Infrastructure interdependencies

In one of the earlier frameworks, Rinaldi et al. [25] distinguish four distinct types of infrastructure interdependencies: physical, cyber, spatial, logical. Material input-output processes are characterized as physical interdependencies. In cyber interdependencies, the exchanged materials are information and data. With the increased coupling of ICT and infrastructure systems, physical and cyber interdependencies were recently combined under functional interdependency [26].

Spatial interdependency refers to the geographical proximity and collocation of infrastructure systems, such as physical sharing of networks, infrastructure components, and space [27]. Logical interdependency was previously used to discuss infrastructure interdependencies caused by social dimensions (i.e. policy, market, etc.). However, researchers discerned that compacting social components under one category does not provide enough nuance to discuss the complex social interactions present in infrastructure transitions. Therefore, new interdependency categories were added such as policy/procedural, societal [28], economic/budgetary, and market interdependencies [29].

The advantages of considering infrastructure interdependencies is acknowledged in the literature; however, achieving a comprehensive overview of these interdependencies is challenging. Previous studies that focused on urban interdependencies often offer conceptual works which can advance the quality of future transition research yet lacks the approachability to influence a direct positive change in urban decision-making [30]. There has been research to identify types and interactions of infrastructure interdependencies but these research consists of either theoretical papers on identification and categorization of interdependencies over a limited number of technologies [23,27,31,32], mathematical papers on how to model and simulate infrastructure interdependencies without a deeper connection to socio-technical dimensions in cities [26,33–36], or explorative papers on the resilience of critical interdependent infrastructure systems against landscape disruptions [37–40]. This is understandable because the topic is complex due to the high interconnectivity between system elements; thus, researchers have to distinguish and focus on a relevant boundary to highlight a specific facet of infrastructure interdependencies.

Due to the complexity of the topic and broadness of the system boundary, there is a fundamental difference between disciplinary and transdisciplinary studies that investigate interdependencies [41]. Transdisciplinary researchers often focus on explaining complex interactions and causal mechanisms rather than attempting to pinpoint how interdependencies can behave and influence the system at large. On the other hand, disciplinary studies provide certainty, accuracy and precision in their research by providing more specific answers to research questions that are more narrowly defined. Combining transdisciplinary approaches with disciplinary studies has been increasingly encouraged in recent years because it would allow a holistic understanding of infrastructure systems [41]. This would call for synthesizing the disciplinary knowledge that engineers have generated with a transdisciplinary lens [42]. Even then, it is not likely to arrive at a single, uniform definition, framework, or typology of infrastructure interdependencies, because the usefulness of any framework will depend on the context in which it is applied [43].

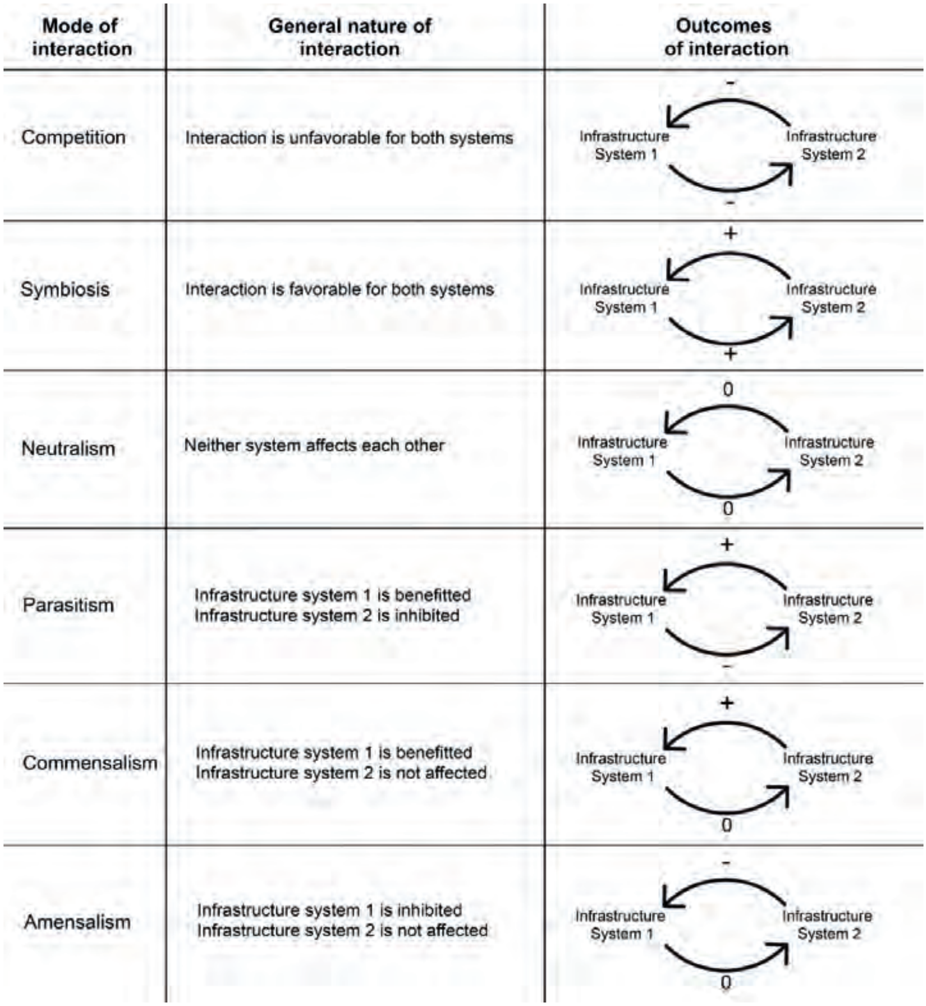

Figure 1 - Multi-mode relationship framework (adapted from [51]).

There have been some studies that explored infrastructure interdependencies in urban sustainability transitions from a socio-technical standpoint [20,23,24,27,44]. To understand infrastructure interdependencies, it is important to note that infrastructure systems are structurally coupled with their socio-technical context [43]. In other words, the context influences infrastructure systems and infrastructure systems influence their context. Interdependencies often cross system or sector boundaries [4]. Notably, UKCRIC has applied systems mapping to understand developments in the built environment and infrastructure systems in the United Kingdom [20]. Similarly, we aim to lay the foundation towards a broad and accessible infrastructure interdependency framework to support transdisciplinary interaction and communication for accelerating urban climate-mitigation in the Netherlands and beyond. We utilize and build on infrastructure interdependency categorization studies to explore recent examples of socio-technical interdependencies within the Dutch urban environment and literature, discuss their implications on urban climate-mitigation, and, finally, suggest an up-to-date, systemic, and accessible framework to enhance multi-disciplinary communication between infrastructure experts, urban planners, and scientists. In this study, we synthesize knowledge from previous frameworks to characterize and explain infrastructure interdependencies based on the outcomes of interactions as shown in **Figure 1**. It is important to note that we do not aim to use these frameworks to exhaustively map interdependencies, but rather aspire to synthesize and utilize these frameworks in order to take a next step in untangling the complexity of infrastructure interdependencies in urban decision-making in the context of sustainability transitions.

Methodology

In this paper, we conduct an exploratory study on recent developments in Dutch urban infrastructure systems and their interdependencies. We aim to bring together a range of infrastructure interdependency and socio-technical systems frameworks, discuss the latest infrastructure interdependency examples with an up-to-date framework, offer an accessible shared-language for infrastructure interdependencies for infrastructure experts, urban planners, and researchers, and thus support the investigation and recognition of influential infrastructure interdependencies for better informed urban sustainability transition decision-making and research. For the data collection, we used document reviews and semi-structured interviews. We identified infrastructure interdependencies with open codes by using the Dutch urban infrastructure transition as our point of reference. We collected data from three sources: a document review of the Dutch climate agreement (KlimaatAkkoord), document reviews of three Dutch urban projects, and semi-structured interviews with stakeholders of the Dutch urban sustainability transition [45]. We also looked for potential interdependencies in the literature if there was not a concrete interdependency example from the Netherlands to motivate future research and investigation. For the data analysis, we used axial codes to categorize types of infrastructure interdependencies and their interactions [46]. Finally, we bring together the different types of infrastructure interdependencies in a framework and discuss their implications for urban climate mitigation. **Appendix A** provides information about our research data folder and **Appendix B** offers more information on the data collection and analysis methods.

Case study

To study relevant infrastructure interdependencies in the context of urban sustainability transitions, we focus our research on The Netherlands. The Netherlands has high urbanization rates, high density of infrastructure services, and limited urban space. Being a densely populated country, the urbanization rate of the Netherlands is 92%, far more than the global average [47]. High urbanization rates result in limited urban space for infrastructure services to match demand. The two main Dutch climate goals are to reduce CO_2 emissions by 49% by 2030 compared to 1990 and climate-neutrality by 2050 [48]. Achieving these goals would mean a significant reshaping of the Dutch urban environment and infrastructure systems. These factors make it likely to encounter a myriad of infrastructure interdependencies in the Dutch context. Moreover, the Netherlands is considered to be one of the notable players for climate mitigation efforts due to their reworked research, development, innovation, and demonstration policies in a document called the "KlimaatAkkoord" (climate agreement) that facilitate the early-stage market deployment of emerging technologies [49]. Thus, it is safe to assume that we can encounter relevant recent examples of infrastructure systems and their interdependencies by investigating the Netherlands.

Data collection

To ensure a broad investigation of infrastructure interdependencies, we study strategic and operational documents on urban sustainability transitions. Strategic documents that discuss future infrastructure plans are important because infrastructure interdependencies can change and occur over a long-time horizon due to their long life cycles [6] and the potential reconfigurations in the system structures [14]. Operational documents are also important because recent infrastructure interdependencies can influence the current socio-technical configuration and lead to a change in the system structure. For the strategic document, we reviewed the KlimaatAkkoord. To lower greenhouse gas emissions, the Netherlands have negotiated the KlimaatAkkoord in 2019, a publicly available public policy document, which identifies current and future technologies, Dutch climate goals, approximately 100 public and private actors, and policy mechanisms [48]. The KlimaatAkkoord contains essential information to investigate infrastructure interdependencies in the Dutch urban sustainability transition: how technologies are planned to be used together, which technologies are expected to compete with each other, infrastructure projects' decision processes, transition actors and institutions, and outcomes of interests pertaining to the infrastructure transition. The KlimaatAkkoord provides an overview of the ongoing infrastructure transition from the perspective of its contributing and affected actors. For the operational documents, we selected publicly available documents from three Dutch urban projects that involve multiple infrastructure technologies to investigate interdependency examples in action: Merwede (Utrecht), 't Ven (Eindhoven), and CityZen (Amsterdam). These projects can be considered flagship projects and are considered important for the Dutch urban transition, which makes them relatively accessible and well documented, providing ample data for our analysis. More information on the urban project selection can be found via the data folder in **Appendix A**.

We complement the document analysis with a round of interviews. Semi-structured interviews grant a certain amount of flexibility in the interview design in addition to having a reasonable structure that is consistent for the data analysis [45]. For this paper, we conducted 10 semi-structured interviews. The initial set of interviewees were identified as representatives of important actors mentioned in the KlimaatAkkoord. After the initial interviews, we used snowballing to reach other participants that have expertise and information on the investigated infrastructure systems examples. Interviews took place between February-July 2021 and their duration varied between 40 to 70 minutes. More information on the research participants and their contributions can be found in the **Appendix B** and attached data folder.

Data analysis

We searched for current and future infrastructure systems and their interdependencies in the context of Dutch urban areas (see **Appendix A** for a short summary of the Dutch urban transition). We started with open codes to identify different types of infrastructure interdependencies that influence urban climate mitigation. Axial codes were constructed to compare, contrast, and categorize interdependency types and their interactions [50]. We use the multi-mode relationship framework [51,52] to identify interactions between infrastructure systems. The multi-mode framework provides a rich setting for discussing interactions amongst systems due to high interconnectivity [14]. We synthesize and build on a range of infrastructure interdependency frameworks [23,25–29,31,37]. By reiterating through interdependencies and their implications with examples from the Netherlands and literature, a coding tree was developed. We used the resulting coding tree in **Figure 2** to categorize infrastructure interdependency types and present related examples to discuss how they can influence urban sustainability transitions. Notwithstanding, technical and social interdependencies can rarely be separated. It is virtually impossible to categorize one interdependency as technical or social since socio-technical systems are often intertwined. Thus, we would like to underpin that these overlapping categories illustrate more of a disposition than a distinction. Often, infrastructure interdependencies occur simultaneously and could influence other social and technical elements.

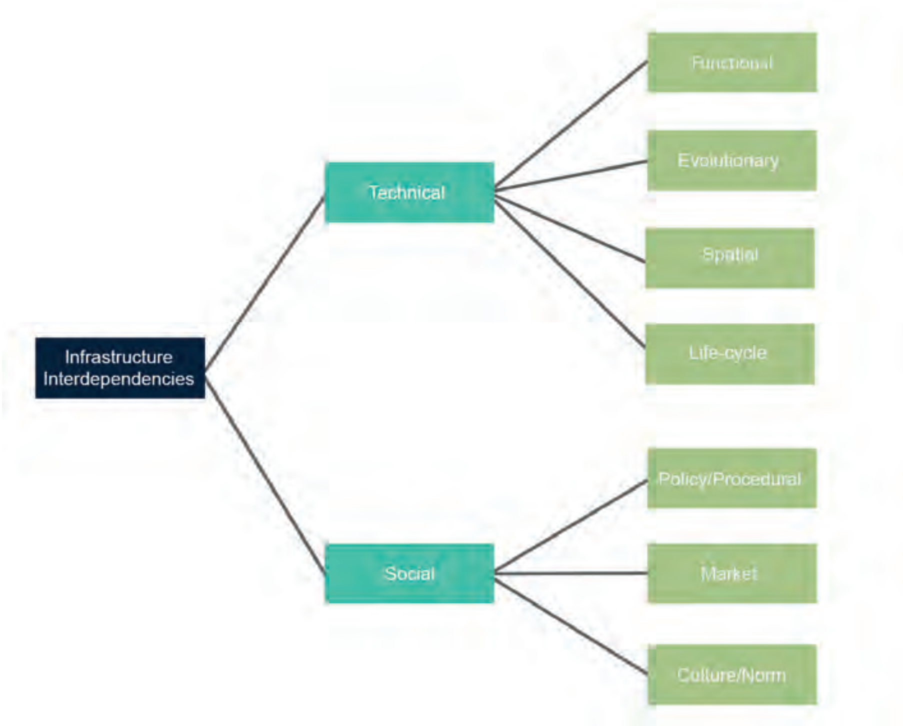

Figure 2 - Infrastructure interdependency types coding tree

Results

We investigated 25 infrastructure systems identified in the Dutch policy document KlimaatAkkoord under Energy, Heating, and Mobility sectors. In **Table 1,** we mapped 300 distinct multi-modal interactions amongst 25 infrastructure systems. **Table 1** confirms that infrastructure systems are thoroughly interconnected. Infrastructure investments are rarely isolated decisions; in fact, each infrastructure decision influences almost all infrastructure systems. In the next sections, we elaborate on interdependency types and interactions, and their implications for the urban sustainability transitions with examples.

Functional interdependency

Functional interdependencies occur when interconnected infrastructure systems have complementary or competing functions which influence the functionality of both systems [26]. Functional interdependencies arise due to material inputs-outputs, information exchange, and complementary/competing functions. In a symbiosis mode, two systems support each other to complete their functions or reveal latent ones. In competition mode, two systems compete with each other to satisfy the same service and hinder each other's capability to satisfy their functions. In parasitism mode, one system replaces the other system by increasing its capability to satisfy that infrastructure service. In the face of the global supply uncertainty, the functional interdependency becomes increasingly important because it is complicated to maintain the balance between supply and demand for material input-outputs of interdependent infrastructures [53].

To illustrate a symbiosis example, in the Merwede project [54], roof-top solar photovoltaic (PV) panels supply approximately 80% of the electricity demand for the geothermal and aquathermal systems that provide heating to the residential complex. However, solar panels produce a significant amount of energy during summer, while heating demand is higher during winter. In Merwede, electricity from panels is used to supply heat with geothermal and aquathermal systems and then the heat is stored in aquifers (ATES – aquifer thermal energy storage) to be used in colder periods. In this way, generated electricity is not sold back to the grid when there is a surplus of solar generated energy in summer (and thus lower energy prices), rather it is stored for when there is a higher heating demand. By providing electricity, solar PV complements aquathermal and geothermal systems and thus reveal a latent function: the system can partly function off-grid to mitigate emissions. ATES complements the aquathermal and geothermal systems by storing the energy for increased self-sufficiency. Since the electricity and heating services in the Netherlands are still mostly supplied by fossil resources [49], the functional symbiosis between solar PV, geothermal, aquathermal, and ATES systems would reduce the overall emissions for heating the Merwede residential complex due to complementing their functions.

To illustrate a parasitic example, natural gas has been one of the influential energy resources in the Netherlands due to the gas fields in Groningen. In 2018, 71% of the heat demand from residential areas and 48% of the service sector were satisfied by natural gas [49]. Heat pumps, on the other hand, have attracted an interest as an efficient alternative heating system in the Netherlands [55] due to changes in the socio-technical landscape and regime. Earthquakes in Groningen (landscape) and policies such as the Dutch climate goals (regime), have led to the decision to phase out natural gas in electricity and heat production in the Netherlands [48]. Since heat pumps and natural gas combi-boilers both satisfy the same heating function, heat pumps could be one of the alternatives that can replace natural gas combi-boilers in households. If a system can replace or reduce the consumption of natural gas to satisfy the same heating need, then that system can parasitize the functions of natural gas in heating systems. Heat pumps, district heat networks, and solar thermal panels are examples of natural gas parasitism.

Evolutionary interdependency

Evolutionary interdependencies occur when an infrastructure system have certain evolutionary characteristics that interact with the other infrastructure systems and/or existing urban socio-technical configurations. The concept of technological trajectory indicates that technologies advance within their evolutionary pathways which originate from systems' accumulated characteristics [15]. Evolutionary characteristics of infrastructure systems consist of technical roots of technologies, accumulated R&D [15], problem solvers that define "relevant" problems [56], users and markets that influences the boundary of "relevance" with their choices [7], and policies and governance structures that influence the infrastructure systems and their markets [17]. Differences in evolutionary characteristics create diverging technological trajectories whereas complementing evolutionary characteristics could lead to spill-over of R&D between infrastructure systems. An emerging infrastructure system can (or cannot) replace an incumbent system on the condition that the previous urban and infrastructure co-evolution and the current socio-technical configuration allow this system change. This interdependency discusses the interconnections between the evolutions in the infrastructure technologies and urban environment. In a symbiosis mode, an advance in one system spills over to another system due to shared evolutionary characteristics. Commensalism can occur when two systems have diverging technological trajectories; hence, developments in one system would only positively affect that system and not affect the other[1].

To illustrate a symbiotic example between infrastructure systems, solar PV and wind energy share certain evolutionary characteristics. They both utilize intermittent natural resources to generate electricity (technical roots). The most

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1. Although we discussed R&D in one system does not affect another system in the commensalism example, as **Table 1** clearly shows, infrastructure systems are heavily interconnected. This means that, R&D spill-over can still occur as second or third order effects. Conducting more research on interdependencies could reveal these effects.

Table 1 - Infrastructure Interdependency Matrix

	Electricity								Heating – individual				
	Solar	Wind	Biomass (Electricity)	Natural Gas (Electricity)	Smart Grid	Electric Batteries	Hydrogen Electrolysis	Hydrogen Storage	Biogas injection	Hydrogen injection	Heat pumps (individual)	Solar Thermal (individual)	Natural Gas (Heating)
Solar		FS, ES, MCP	FCP, PCP	FP, MCP	FS, ES, MS, PCP, CNS, CNCP	FS, ES, MS, PCP, CNS, CNCP	FS, ES, MS	FS	PCP	ES	FS,MCP	FS, ES, SS	FP, MCP
Wind	FS, ES, MCP		FCP, PCP	FP, MCP	FS, ES, MS, PCP, CNS, CNCP	FS, ES, MS, PCP, CNS, CNCP	FS, ES, MS	FS	PCP	ES	FS,MCP	NT	FP, MCP
Biomass (Electricity)	FCP, PCP	FCP, PCP		FP	FS	FS	FS, ES	FS	FS, ES	FS, ES	FS	FS	FP
Natural Gas (Electricity)	FP, MCP	FP, MCP	FP		FS	FS	FS, ES	FS	ES, SS, CNS	ES, SS, CNS	FS, ES	FS	ES, SS
Smart Grid	FS, ES, MS, PCP, CNS, CNCP	FS, ES, MS, PCP, CNS, CNCP	FS	FS		FS, ES, MS, PCP, CNS, CNCP	FS, ES, MS	FS	FS	FS	FS	FS	FS
Electric Batteries	FS, ES, MS, PCP, CNS, CNCP	FS, ES, MS, PCP, CNS, CNCP	FS	FS	FS, ES, MS, PCP, CNS, CNCP		FS, ECM	FS, ECM	ES	FS, ECM	FS	FS	NT
Hydrogen Electrolysis	FS, ES, MS	FS, ES, MS	FS, ES	FS, ES	FS, ES, MS	FS, ECM		FS, ES, MS	FS, ES	FS	FS	FS	FCP
Hydrogen Storage	FS	FS	FS	FS	FS	FS, ECM	FS, ES, MS		ES	ES, FS	FS	FS	FCP
Biogas injection	PCP	PCP	FS, ES	ES, SS, CNS	FS	ES	FS, ES	ES		ES, SS	FS	FS	SS, FP
Hydrogen injection	ES	ES	FS, ES	ES, SS, CNS	FS	FS, ECM	FS	ES, FS	ES, SS		FCP	FS	SS, FCP
Heat pumps (individual)	FS,MCP	FS,MCP	FS	FS, ES	FS	FS	FS	FS	FS	FCP		FS	FS
Solar Thermal (individual)	FS, ES, SS	NT	FS	FS	FS	FS	FS	FS	FS	FS	FS		FS
Natural Gas (Heating)	FP, MCP	FP, MCP	FP	ES, SS	FS	NT	FCP	FCP	SS, FP	SS, FCP	FS	FS	
Heat pumps (central)	FS	FS, MCP	FS	FCP, ECM	FS	FS	FS	FS	FS	PCP, FCP, SCP	ES, FS	FS	FS, FP
Biomass plant	FCP, PCP, ECM	FCP, PCP, ECM	FS, ES, SS	FP	FS	FS	PCP	PCP, FCP	ES	PCP, FCP, SCP	FCP	FS	FP
Aquathermal	FS, PCP	FS, PCP	PCP	ECM	FS	FS	FS, FCP, PCP	PCP, FS, FCP	FCP, PCP, SCP	PCP, FCP, SCP	FCP, FS, ES	FS	FP
Geothermal	FS, PCP	FS, PCP	PCP	ECM	FS	FS	FS, FCP, PCP	PCP, FS, FCP	FCP, PCP, SCP	PCP, FCP, SCP	FCP, FS, ES	FS	FP
Residual Heat	PCP	PCP	PCP	ECM	FS	FS	PCP	PCP, FCP	FCP, PCP, SCP	PCP, FCP, SCP	FS, FCP	FS	FP
District Heating	FS	FS	FS	FS, LS	FS	FS	ECM	FCP	FCP, PCP, SCP	SCP, FCP	FS, FCP	FS	FS
Solar Thermal (central)	FS, ES, SS	NT	FS, PCP	FP	FS	FS	FS	PCP, FCP	FCP, PCP, SCP	PCP, FCP, SCP	FS, FCP	ES	FS
Seasonal Heat Storage	FS	FS	FS	FS	FS	NT	ECM, FCP	ECM, FCP	FCP	SCP, FCP	FS	FS	FS
Biofuel	ECM	ECM	ES	ECM	ECM	ECM, FS	ECM	ECM	ES	ECM	ECM	ES	ECM, FS
Hydrogen Fuel	ECM, FS	ECM, FS	ECM, FS	ECM	EB, FS	ECM, ES, FS	ES, FS	ES, FS , ECM	ECP, ES, FS	ES	ECM	ES	ECM, FS
Electric Car Battery	ES, FS, MS, CNCP, PCP, MCP	ES, FS, MS, CNCP, PCP, MCP	ECM, FS	ECM, FS	ES, PCP, FS, MS, CNCP	FS, ES, MS, CNS, CNCP	ECM, ES, FS	ECM, ES, FS	ECM	ECM	ES, FS, MCP	ES	ECM, FS
Fossil Fuel	ECM, MCP	ECM, MCP	ECM	ES	ECM	ECM	ECM	ECM	ECM	ECM	ECM	ECM	ES

	Heating – central								Mobility			
	Heat pumps (central)	Biomass plant	Aquathermal	Geothermal	Residual Heat	District Heating	Solar Thermal (central)	Seasonal Heat Storage	Biofuel	Hydrogen Fuel	Electric Car Batteries	Fossil Fuel
Solar	FS, MCP	FCP, PCP, ECM	FS, PCP	FS, PCP	PCP	FS	FS, ES, SS	FS	ECM	ECM, FS	ES, FS, MS, CNCP, PCP, MCP	ECM, MCP
Wind	FS, MCP	FCP, PCP, ECM	FS, PCP	FS, PCP	PCP	FS	NT	FS	ECM	ECM, FS	ES, FS, MS, CNCP, PCP, MCP	ECM, MCP
Biomass (Electricity)	FS	FS, ES, SS	PCP	PCP	PCP	FS	FS, PCP	FS	ES	ECM, FS	ECM, FS	ECM
Natural Gas (Electricity)	FCP, ECM	FP	ECM	ECM	ECM	FS, LS, LA	FP	FS	ECM	ECM	ECM, FS	ES
Smart Grid	FS	FS	FS	FS	FS	FS	FS	FS	ECM	EB, FS	ES, PCP, FS, MS, CNCP	ECM
Electric Batteries	FS	FS	FS	FS	FS	FS	FS	NT	ECM, FS	ECM, ES, FS	FS, ES, MS, CNS, CNCP	ECM
Hydrogen Electrolysis	FS	PCP	FS, FCP, PCP	FS, FCP, PCP	PCP	ECM	FS	ECM, FCP	ECM	ES, FS	ECM, ES, FS	ECM
Hydrogen Storage	FS	PCP, FCP	PCP, FS, FCP	PCP, FS, FCP	PCP, FCP	FCP	PCP, FCP	ECM, FCP	ECM	ES, FS , ECM	ECM, ES, FS	ECM
Biogas injection	FS	ES	FCP, PCP, SCP	FCP, PCP, SCP	FCP, PCP, SCP	FCP, PCP, SCP	FCP, PCP, SCP	FCP	ES	ECP, ES, FS	ECM	ECM
Hydrogen injection	PCP, FCP, SCP	PCP, FCP, SCP	PCP, FCP, SCP	PCP, FCP, SCP	PCP, FCP, SCP	SCP, FCP	PCP, FCP, SCP	SCP, FCP	ECM	ES	ECM	ECM
Heat pumps (individual)	ES, FS	FCP	FCP, FS, ES	FCP, FS, ES	FS, FCP	FS, FCP	FS, FCP	FS	ECM	ECM	ES, FS, MCP	ECM
Solar Thermal (individual)	FS	FS	FS	FS	FS	FS	ES	FS	ES	ES	ES	ECM
Natural Gas (Heating)	FS, FP	FP	FP	FP	FP	FS	FS	FS	ECM, FS	ECM, FS	ECM, FS	ES
Heat pumps (central)		FCP,PCP	FS, ES, PCP	FS, ES, PCP	FS, PCP	FS	FS	FS	ECM	ECM	ES, MCP	ECM
Biomass plant	FCP,PCP		PCP, FS, FCP	PCP, FS, FCP	PCP, FCP	FS	FS, FCP	FS	ES	ECM, FS	ECM, FS	ECM
Aquathermal	FS, ES, PCP	PCP, FS, FCP		ES, FS, PCP	PCP, FCP	FS	FS	FS	ECM	ECM	ES	ECM
Geothermal	FS, ES, PCP	PCP, FS, FCP	ES, FS, PCP		PCP, FCP	FS	FS	FS	ECM	ECM	ES	ECM
Residual Heat	FS, PCP	PCP, FCP	PCP, FCP	PCP, FCP		FS	FS	FS	NT	NT	NT	NT
District Heating	FS	FS	FS	FS	FS		FS	FS	NT	NT	NT	NT
Solar Thermal (central)	FS	FS, FCP	FS	FS	FS	FS		FS	ECM	ECM	ES, FS	ECM
Seasonal Heat Storage	FS	FS	FS	FS	FS	FS	FS		NT	NT	NT	NT
Biofuel	ECM	ES	ECM	ECM	NT	NT	ECM	NT		FCP, FS, ECM, SS	FCP, FS, ECM	FP, ECM
Hydrogen Fuel	ECM	ECM, FS	ECM	ECM	NT	NT	ECM	NT	FCP, FS, ECM, SS		FCP, ECM	FP, ECM
Electric Car Battery	ES, MCP	ECM, FS	ES	ES	NT	NT	ES, FS	NT	FCP, FS, ECM	FCP, ECM		FP, ECM
Fossil Fuel	ECM	ECM	ECM	ECM	NT	NT	ECM	NT	ECM	FP, ECM	FP, ECM	

Legend

Infrastructure systems

Sector		Infrastructure System
Electricity		Solar Photovoltaic
		Wind energy
		Biomass electricity plants
		Natural gas electricity plants
		Smart-grids
		Electrochemical batteries
		Hydrogen electrolysis
		Hydrogen storage (caverns & tanks)
Heating	Household	Biogas injection
		Hydrogen injection
		Heat pumps (household)
		Solar Thermal (household)
		Natural Gas heat plants
	Central	Heat pumps (central)
		Biomass heat plants
		Aquathermal energy
		Geothermal energy
		Residual heat
		District heating networks
		Solar Thermal (central)
		Seasonal heat Storage
Mobility		Biofuel
		Hydrogen fuel
		Electric car battery
		Fossil fuel

Infrastructure interdependency types

Type name	Abbrevation
Policy/Procedural	P
Market	M
Culture & Norm	CN
Spatial	S
Evolutionary	E
Functional	F
Life-cycle	L

Multi-mode interactions

Interaction name	Abbrevation
Symbiosis	S
Competition	CP
Parasitism	P
Commensalism	CS
Amensalism	A
Neturalism	N

Color codes

Color	Meaning
(white)	Dutch example
(grey)	Literature example

relevant problem for both solar and wind is the intermittent and volatile electricity supply (paradigm of engineers). They require functionally symbiotic storage systems (i.e. electric batteries, hydrogen storage) to utilize them in an efficient manner (demand of users and markets). Therefore, solutions towards solving intermittency problems (accumulated knowledge) would support both systems in how they can provide uninterrupted power (technical trajectory). Due to having similar evolutionary characteristics, solar PV and wind energy are in an evolutionary symbiosis. Evidently, the KlimaatAkkoord [48] puts forth integrated plans and goals for both solar and wind electricity generation since they both provide intermittent renewable electricity and are in need of complementing base-load systems.

For a commensalism example, electrochemical batteries have a divergent evolutionary pathway from hydrogen electrolysis. Electrochemical batteries convert electricity to chemical energy whereas hydrogen electrolysis converts electricity into hydrogen (technical roots). Electrochemical batteries can only store energy for a short period of time and require scarce elements to be built while hydrogen electrolysis is challenged by conversion (in)efficiencies and high costs (paradigm of engineers). Due to diverging paradigms, a breakthrough in one system would not directly affect the development in the other system (accumulated knowledge and trajectory). Due to their divergent evolutionary characteristics, the Netherlands is considering electric batteries for short-term electricity storage and short-distance light-duty urban cars whereas hydrogen is often considered for long-term energy storage and long-distance heavy-duty inter-city travel (demand of users and markets) [48]. Therefore, electric batteries and hydrogen are in an evolutionary commensalism because of diverging evolutionary characteristics. In addition, these two systems are also in a functional symbiosis because both systems have complementary functions in energy storage (short-term vs. long-term) and mobility solutions (short-distance, urban-mobility vs. long-distance, heavy-duty).

For an example of the interdependencies between infrastructure systems and urban environment, we can discuss the expansion of the Rotterdam district heating network and high temperature central heating systems. Rotterdam already possesses one of the larger district heating networks that supplies a high temperature water regime to its users [57]. Although converting the heating networks into a lower temperature system could reduce the overall urban energy consumption, this endeavor is not currently financially, socially, and timing-wise a feasible undertaking. However, expanding the current high temperature network with residual heat supply can reduce urban emissions significantly [58] and Rotterdam can still go through another transition phase when the city is ready (i.e.

insulating buildings, finding finances for energy-efficiency). If Rotterdam expands its already extensive high temperature network, all high temperature central heating systems (i.e. residual heat, geothermal) would benefit from this choice. Consequently, we can argue that there is an evolutionary symbiosis between heating network and all high temperature central heating systems when the urban configuration of Rotterdam is considered. On the other hand, this also means that other low temperature heating solutions (i.e. aquathermal) or individual solutions (i.e. heat pumps) are hindered since the high temperature option is more affordable (evolutionary advantage). This would be an example of parasitism between high temperature and low temperature heating systems. Overall, the previous socio-technical evolutions and current configuration in Rotterdam would influence how infrastructure systems can develop or be adopted within its urban boundary via enabling some systems while hindering others.

Spatial interdependency

Spatial interdependency occurs due to the proximity of infrastructure systems within the urban space and/or geospatial characteristics of urban areas. Each city differs in its opportunities and challenges when its geospatial characteristics and urban space are considered. To illustrate, Rotterdam can easily take advantage of aquathermal systems due to being close to Maas river or the Hague can utilize geothermal energy since it is close to potential wells. In a symbiosis mode, interconnected systems can take advantage of the same infrastructure components, networks or urban space. In competition and parasitism modes, interconnected infrastructure systems compete for the same urban space or certain infrastructure systems are benefited because of the urban geospatial location, leaving less opportunity for other systems.

In the Rotterdam Rozenburg pilot project [59], existing natural gas pipes are used to carry a form of hydrogen called synthetic natural gas (SNG). A hydrogen-ready boiler uses the delivered hydrogen to provide heating to 25 houses with back-up natural gas boilers. Lessons learned from this project will be used in the heating project in another region where 550 residential houses will be heated 100% by hydrogen by utilizing the existing natural gas pipes [60]. Hydrogen and natural gas share certain technical characteristics: they are both gaseous energy carriers which allow conversions amongst them. The Rozenburg example illustrates a spatial symbiosis since hydrogen can use the network of natural gas which, then, leads to several functional advantages for both systems. For instance, natural gas boilers can supply peak demands if the hydrogen from intermittent sources is not sufficient which, contrarily, can prolong the natural gas consumption. Overall, green gas alternatives, such as hydrogen or biogas, are in spatial symbiosis with natural gas and can provide sustainable heating pathways and alternatives for Dutch cities because the Netherlands can utilize and build on its existing natural gas industry and networks.

One heating solution that the Netherlands considers is the coupling of district heating networks with central heating systems [48]. Due to limited underground space in Dutch urban areas [61], investing in district heating in certain areas might require the removal of redundant gas pipes. In the 't Ven project, underground space is even more constrained since the heating network provides varying temperature regimes with multiple supply-return pipes to accommodate different household demands (high-temperature supply for poorly-insulated and radiator-heated houses vs. low-temperature supply for highly-insulated and floor-heated houses). Therefore, heating networks and natural gas systems are in spatial competition with each other since both compete for the same finite underground space.

District heating can also be designed as open systems which can lead to spatial symbiosis. In such systems, multiple heat systems (i.e. biomass boilers, or aquathermal heat-pumps) connect to the same "open" network to supply heat. In open networks, hard-to-scale heating solutions would be in functional symbiosis by providing each other flexibility and uninterrupted heat supply to the district. Furthermore, transition or phased-out systems could be used in open networks until renewable solutions scale up and crowd-out polluting systems. In this mode, heating networks provide a spatial symbiosis with a number of central heating solutions to provide flexible transitions in heating systems.

To illustrate an example for the urban geospatial qualities, Rotterdam has an easy access to the Maas river, allowing the connection of aquathermal systems to heating networks whereas an inland city like Tilburg can couple the existing biomass and hard-coal fired power plant in the nearby region to the district heating [62]. In Rotterdam, the symbiosis between heating network and aquathermal would be much more stronger [57] whereas the symbiosis between biomass and district heating systems would be much stronger in Tilburg when the differing urban geospatial opportunities are considered. Overall, infrastructure systems become an influential part of the urban space by shaping and being shaped by the existing urban configuration.

Life-cycle/Temporal interdependency

Life-cycle/Temporal interdependencies occur due to differences in technological life-cycle stages [9] and product lifespans [63] as well as existing contracts for system use [64]. Effects of this interdependency type become more apparent due to the urban temporalities that influence a change on the socio-technical systems [30], such as with phasing-out or transitioning[2] systems. To illustrate, when an infrastructure system starts to stagnate because of reaching the end of its life-cycle, this temporal opportunity can benefit other sustainable emerging infrastructure systems by leading to *windows of opportunities* [7] and a "system renewal and transition" stage [9]. In contrast, an incumbent infrastructure system can prolong its life-cycle by using its evolutionary advantages because other emerging systems might not have reached the same evolutionary level because of their earlier life-cycle stages. A time-dependent interdependency matters because interdependencies are not static occurrences but instead they evolve as a result of developments and changes in the urban paradigm [30].

Depending on the material and soil quality, natural gas pipelines require periodic maintenance/replacement to function efficiently. If the pipeline maintenance/replacement costs are extensive, it becomes feasible to switch to alternative systems for phasing out of gas. One of the criteria for selecting the 't Ven neighborhood for a transition plan [65] was the necessity of replacing old gas pipes. As mentioned, heating networks require the underground space occupied by the natural gas pipelines on account of their spatial competition. In the 't Ven project, the ending lifespan of pipes coincided with Eindhoven's heat transition plans and thus an alternative solution, district heating network, became more attractive due to high replacement costs. This illustrates a life-cycle symbiosis between natural gas and heating network. In this case, the natural gas' ending product lifespan (old pipes in Eindhoven) opened the way for a system renewal through a district heating system.

Unless there is a concrete exit-strategy for a transitioning or phasing-out of a system, transition processes could be undermined, eventually stall, and result in lock-ins [14]. If a vital infrastructure system is phased-out, its interdependent systems could suffer from losing their symbiotic functions. Furthermore, societal

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2. Transitioning system, in this section, means: a technology, fuel or system that can substitute carbon emitting systems in the short and medium term [14]. They are not considered as "destination" technology, fuel, or system because they have their own evolutionary challenges in the long-term. Thus, transitioning system acts as a bridge in between carbon-emitting systems and destination systems. To give a transition fuel example, we can discuss using natural gas to replace coal [14]. For a transition technology example, using biomass to replace high temperature coal demand before carbon-neutral technologies emerge can be considered [48].

functions of interdependent systems could be so vital that the decision to phase out polluting systems could even be postponed. To illustrate, the sustainability of heating networks is heavily influenced by the choice of heat supply. Currently, 69% of the heat supply for the Dutch heat distribution networks comes from excess heat from fossil power plants, mostly natural gas. Even some of the district heating projects with fossil systems began supplying heat after 2000 (i.e. natural gas combined heat and power in 2009 in Delft and Lansingerland) [62]. All infrastructure projects and contracts require a period where investors can receive returns on their investments. This might take decades before a satisfactory return on investment is realized depending on the investment scale and affordability of the heat costs for consumers [66,67]. Therefore, new contracts for coupling natural gas with the district heating network would demand that these fossil heat sources need to be kept operational until the contract ends even though natural gas systems are being phased out. Otherwise, breaking such contracts might lead to stranded assets, activate contract-breach clauses, and eventually cost more to the society [68]. This can be seen as an example of life-cycle amensalism or parasitism. Fossil fuel based heating systems could protect (amensalism) or improve (parasitism) their position and incumbency by prolonging their consumption in bundled systems such as in the fossil coupled heating network example described above and thus can crowd-out alternative heating solutions (i.e. geothermal, aquathermal coupled heating networks etc.) unless a concrete exit strategy for natural gas exists.

Policy/Procedural interdependency

Urban values guide urban actors and institutions to create the policy instruments to bring about the intended urban change. However, urban values can be diverse, be perceived divergently by different actors, change their meaning throughout the decision-making stages, and, most importantly, serve conflicting societal needs and goals [10]. Urban actors and institutions construct the selection mechanism that makes an urban value "relevant" which, in turn, affects how policy instruments are designed [69]. Consequently, the gap between the dynamic urban values and climate mitigation goals can lead to unintended policy effects that can work against initial policy aims [70]. This is one of the underlying reasons why policy/procedural interdependencies occur. This interdependency originates because infrastructure systems affect each other due to existing policies, regime actors, institutions, and procedures. Through their targets and designs, policies can create an environment in which certain infrastructure systems benefit and others are hindered. Infrastructure systems influence each other on account of which system was included in a policy action (or not), the level of incentives for certain systems over others, and the time-frame for policy activities.

In the Dutch sustainable energy subsidization scheme SDE++ [71], almost all subsidized heating alternatives are central heating systems (i.e. aquathermal, industrial heat pumps, or biomass combined heat and power plants) except the green gas injection to the natural gas grid, a tailored niche solution where other alternatives are not available [72]. Due to complementing functions, central heating systems and district heating networks are in functional symbiosis: central heating systems require a delivery channel and district heating needs a hot water supply [73]. The current preference for central heating systems implies that investments towards district heating systems should also be expected to benefit from the subsidized central heating systems. This example illustrates a policy/procedural symbiosis between central heating solutions and district heating networks due to the design of the SDE++ scheme. Although there are no direct subsidies for heating networks, the preference for central systems would spill-over to the district heating systems through projects involving these functionally complementing systems.

Although open district heating systems offer spatial symbiosis by integrating sustainable heat supply systems, these systems have not developed in the Netherlands due to the existing ownership configuration. Often, network operators are also the heat suppliers. In many Dutch regions, contracts for heating networks were tendered. The competitive tendering stimulated network operators to negotiate long-term contracts with own fossil fuel based heat sources which in turn creates substantial market entry barriers for emergent alternative low-carbon heating systems [74]. District heating networks are attractive heating systems that can reach a large customer base with ease while ensuring profitability [74]; hence, they are able to support emerging heating systems to scale their production. However, emerging heating systems experience a market entry barrier since the incumbent heat suppliers also own the rights for the heat distribution [74]. This is a good example of policy/procedural competition: alternative heating systems can be crowded-out if current heat suppliers (and network operators) use the existing ownership configuration and refuse or delay the connection of functionally competing heating systems in these open networks. Although the current policy paradigm calls for more open heating markets to reduce urban heating emissions [71], the current ownership design for district heating systems does not allow this. Overall, policy/procedural interdependency occurs because policies and procedures favor certain systems and actors; then, this predisposition spills over positively to some systems and actors while affecting others negatively.

Market interdependency

Configurations and perceptions of infrastructures service markets are rapidly changing due to the globalization, digitization, and decentralization trends. First, the globalization of the world's economy and digitization of infrastructure services are bringing spatially separated infrastructure services closer [29]. Changes in one of the energy and infrastructure service markets could essentially have indirect effects in other markets [14]. Although it is impossible to treat all national energy markets as one single global market (given the myriad socio-technical elements and vague boundaries), it is also as hard to ignore the effects of overlapping influences between urban, regional, and national markets. Digitized and decentralized energy systems are progressively becoming more interconnected patchworks of energy markets, that operate on top of the national infrastructure hardware [75]. The market interdependency discusses these effects by focusing on how market configurations at different scales create interconnections between infrastructure systems.

Smart grids can support the emergence of intelligent decentralized energy markets that reveal latent functions from cooperating infrastructure systems. In the CityZen project [76], independent solar PVs and electric batteries in different households were cascaded together to form Virtual Power Plants (VPP) that carry out more complex energy interactions than their respective technologies. By treating all batteries as a single electricity storage unit, VPP can either store the electricity until there is a flexibility demand and then transport the electricity to neighborhoods in need or profit from selling electricity in the energy trading markets to reduce the neighborhood's energy costs. In both cases, the cascaded energy system (solar PVs and batteries), ICT systems, and grid system elements (grid operators, networks, and components) come together to create a virtual decentralized energy market to support different functions (i.e. flexibility or energy-trading). Therefore, in this configuration of VPPs, we can see a market symbiosis between solar PVs, electric batteries, and smart grids since they can form a virtual decentralized market, and even a decentralized energy decision-making mechanism, on top of the national hardware and reveal latent functions from interconnecting infrastructures (i.e. providing flexibility). In this example of the market symbiosis, interconnected infrastructure systems form a decentralized market and thus alleviate intermittency problems.

One of the discussed ways to reduce Dutch urban emissions is to transition towards a fully-electrified system to better integrate intermittent renewables [48]. On the end-user side, there will be new loads on the electricity grid due to electric-stoves, heat-pumps, and electric cars [77]. Evidently, daily and seasonal load profiles will vary significantly in an all-electric system. First, new loads in all-electric system can have high and unpredictable instantaneous demand (i.e. fast-charging car batteries connected to the grid simultaneously). In highly renewable systems, the energy imbalances have long time-scales because the systemic over-generation happens in summer by solar PVs whereas the systemic energy deficit occurs in winter due to the increased heat demand [77]. On the supply-side, highly renewable systems can produce a large and flexible intermittent energy but requires other systems that can satisfy the base load to compensate for the unpredictable loads and long-term energy imbalances [77]. As the flexible load becomes significantly large as in highly renewable systems, it is critical to maintain the symmetry between supply and demand [78] and deploy price-responsive technologies [79] to reduce the impact of volatile energy imbalance on prices. If there is a capacity shortage, electricity prices may vary more frequently and in larger ratios as well as leading to price spikes [80]. In this example, using the infrastructure technologies in all-electric systems together (i.e. heat-pumps, solar PV, electric cars) leads to volatile and hard-to-predict price trends in the market which, then, can create barriers for the integration of renewables in the energy system. Hence, these systems are in a market competition since using them together would negatively influence the market's price configuration the market which might hinder the adoption of these systems.

Culture/Norm interdependency

Service users create a symbolic meaning of infrastructure systems and services over time [7]. This symbolic meaning of infrastructure services impact urban transitions through social acceptance, adoption rates, accepted norms around infrastructure service use, and changes in market demands and user habits. Technology users can enable transitions as intermediaries by connecting new technologies and practices to urban life and habits [81]. In contrast, socio-economic and cultural norms can also work against transitions by leaving out the infrastructure systems that cannot conform with the current urban context. This interdependency occurs when existing culture and norms around infrastructure systems and services influence each other. In a symbiosis mode, interconnected infrastructure systems conform or can even transform the existing culture and norms. In a competition mode, interconnected infrastructure systems do not align with existing culture and norms; thus, they might be adopted less or some of their functions can be prevented.

Smart meters exchange the information on the energy flows between grid operator and prosumers as well as informing prosumers of their households' energy balance [76]. In prosumer systems, there is a bi-directional energy and information flow between the grid operator and prosumers compared to the unidirectional flow of energy in traditional centralized electricity systems. The increased interactions and interoperability in smart grids are changing the paradigm of how infrastructure services are perceived and used [82]. In the CityZen project, system users were given a user interface which gave reports on solar generation and in–house consumption. Having access to such an interface has influenced system users to create a habit of checking energy balance, pay more attention to the energy flows of the house, and even investigate energy leaks of the house [76]. If nurtured well, these changes can be cultivated into a stewardship for the environment and ambition for energy autonomy among system users. More research is needed on this topic since the same interdependency could also lead to other cultural implications, such as inclusiveness (tech-literacy) or privacy issues (sharing data). All in all, the CityZen example is a good illustration of culture and norm symbiosis since the user interface influences the habits of prosumers towards energy-conscious behavior and renewable energy integration among urban communities. In this example, cooperating infrastructure systems create a change in social routines which, in turn, influences how these systems and services are used.

In vehicle-to-grid systems (V2G), car batteries provide flexibility to the electricity grid to maximize the utilization of intermittent generation. However, urban temporal rhythms do not exactly match with intermittent solar generation. Electric cars are often charged during evening times when residents return from work. However, the bulk of the electricity production from solar panels happen during the daytime. Thus, there is a time lag between peak demands and intermittent electricity production. In the CityZen project [76], car batteries connected to the V2G system most often provided flexibility to the grid during nighttime. Some of the electric car owners found out that their car battery was not fully charged and experienced delays when they had to go to work in the morning. The dominant 9-5 office-located work culture creates synchronous peak loads in the grid and dictates a time-lag between intermittent generation and peak-loads which, in turn, presents major challenges for the full integration of intermittent sources and electrification of the energy system. Although technologies in smart grids are powerfully interconnected through functional and market symbioses, existing cultural configurations can also prevent expected functions from cooperating infrastructure systems to emerge. In the CityZen's V2G example, solar PV and electric car batteries can provide flexibility but other functions that normally emerge from their cooperation (i.e. provision of mobility or satisfying self-consumption) are hindered because of the urban rhythms. Consequently, systems in smart grids experience a culture and norm competition because V2G systems cannot currently offer their full-functionality due to the predominant urban culture.

Discussion

Except for a few studies [20,23], previous works often focus more on the hindering effect of infrastructure interdependencies than their enabling potential for urban sustainability transitions. Our findings shed light on both hindering and enabling effects of socio-technical interdependencies on urban climate mitigation. On one hand, the examples show that infrastructure interdependencies can work to maintain the status quo, resist well-intentioned policies, prevent functions of interconnected systems, result in stranded assets and sunk costs, or lead to lock-ins. On the other hand, infrastructure interdependencies can also support urban transitions by revealing and satisfying latent societal functions of infrastructures, generating social, economic, evolutionary, and spatial opportunities, leading to spill-over of R&D and investments, and presenting windows of opportunities. To illustrate this point and to signal the relevance of our study, **Table 2** shows a selection of examples where infrastructure interdependencies led to these outcomes.

Infrastructure interdependencies are important to acknowledge because they can hinder or enable urban climate mitigation. Through iterating between the latest examples from the Netherlands and literature, we utilized earlier categorizations of infrastructure interdependencies and built on these frameworks by deliberating up-to-date and systemic explanations of interdependencies and by suggesting new types of interdependencies. Our proposed categorization summarizes the previous work and suggests an accessible and systemic way of looking at socio-technical interdependencies in infrastructure systems which strengthens our understanding of their implications for urban mitigation efforts. Our findings have implications for two themes: urban transitions and infrastructure interdependencies.

Table 2 - Examples for the implications of infrastructure interdependencies

Outcomes of infrastructure interdependencies	Explanations of case examples	Infrastructure interdependency	Multi-mode interaction
Maintain status quo	Heat providers/grid operators can make long-term contracts to utilize fossil-dependent heating systems and thus prolong the fossil consumption in the city.	**Life-cycle amensalism**	- Infrastructure System 1 Infrastructure System 2 0
Policy resistance	Sustainable heating alternatives cannot be embedded to the open disctrict heating network since grid owners are also the main heat providers for the network.	**Policy/Procedural competition**	- Infrastructure System 1 Infrastructure System 2 -
Stranded assets of sunk costs	Breaking an ongoing contract for a coal heated district heating network could lead to stranded assets. Furthermore, if the investment or contract is brand new, this would lead to sunk costs.	**Life-cycle amensalism**	- Infrastructure System 1 Infrastructure System 2 0
Prevent functions of infrastructure systems	Electric cars can act as electric batteries in smart-grids to balance the electricity grid. However, this would mean that the battery of the electric car might be depleted (or charged less than required) at the times of mobility demand.	**Culture/Norm competition**	- Infrastructure System 1 Infrastructure System 2 -
Lock-in	Prolonged consumption of fossil fuels in bundled systems can crowd-out alternative heating systems	**Life-cycle parasitism**	+ Infrastructure System 1 Infrastructure System 2 -
Reveal/satisfy emergent functions	Using solar PVs with central heat pump solutions (i.e. aquathermal or geothermal) could create a self-sufficient heat system where the heating system does not require (or requires less) electricity from the grid.	**Functional symbiosis**	+ Infrastructure System 1 Infrastructure System 2 +
Energy price volatility	Transition towards all-electric energy systems is challenged by long-term energy imbalances which can lead to energy spikes and frequent and significant fluctuations in the energy price.	**Market competition**	- Infrastructure System 1 Infrastructure System 2 -
Influencing user behavior	Interfaces in smart-grids changes the social routines and habits for energy consumption.	**Culture/Norm symbiosis**	+ Infrastructure System 1 Infrastructure System 2 +
Reducing energy costs	Infrastructure systems in smart-grids could profit from selling electricity in the energy trading markets to reduce the neighborhood's energy costs.	**Market symbiosis**	+ Infrastructure System 1 Infrastructure System 2 +
R&D spill-over	A breakthrough in a battery solution would influence both solar and wind systems positively. The R&D in electric batteries spills over to intermittent renewable systems.	**Evolutionary symbiosis**	+ Infrastructure System 1 Infrastructure System 2 +
Redesigning existing systems	Utilizing green gases in already existing natural gas pipe infrastructure does not require as much investments as building a new pipe infrastructure for green gases.	**Spatial symbiosis**	+ Infrastructure System 1 Infrastructure System 2 +
Presenting window of opportunities	Instead of replacing old natural gas pipes with high costs, district heating networks can replace gas pipes to supply heat. If the replacing of gas pipes coincides with the transition plans, this can create a window of opportunity.	**Life-cycle symbiosis**	+ Infrastructure System 1 Infrastructure System 2 +

Urban transitions

The debate on urban interdependencies has been gaining more attention in the last decades. The urban environment can be considered a system of systems or a nexus where a varying range of urban resources flow, urban infrastructure technologies interconnect, and operational, financial, and governance dimensions interface at multiple scales (i.e. national, municipal, household, etc.) [30]. Urban transitions emerge not in isolated individual domains but as a result of co-evolutions within the "fabric of the urban space" [30]. Therefore, the urban system cannot be understood independently from their historical, geospatial, technical and socio-political context [83]. Moreover, this urban context is highly dependent on temporality; in other words, changes in the urban context result in a new reorganization of the urban system and thus lead to path-dependencies, slow incremental changes, sudden emergence/adoption for infrastructure systems. This implies that there is no silver-bullet strategy or infrastructure technology for the global urban climate mitigation efforts but rather each local urban co-evolution results in its own feasible pathways, systems, or policies [84]. Evidently, the cross-sectoral management and co-management of infrastructure systems have been recognized as increasingly essential but the transition actors still tend to focus and act on incremental changes conforming to their jurisdictions and areas of responsibility [40]. Therefore, these cognitive challenges and institutional restrictions hinder the ability for organizing cross-cutting co-management and robust decision-making in urban infrastructure transitions [17,30]. In order to untangle this urban complexity, urban planners should (i) approach infrastructure systems not as bounded and isolated systems but as a system of systems that shape the whole socio-technical paradigm of urban futures [85] (ii) and consider the effects of interconnections, higher order effects, and links across the system boundary [86] over a range of socio-technical dimensions (i.e. policies, markets, technologies, etc.) [7], scales (i.e. government, municipal, households) [87], and urban temporalities [30].

Overall, cities are densely populated compact spaces, a system of systems, where different infrastructure sectors and urban services simultaneously collaborate and compete to ensure the continuity and quality of urban life [88]. The interconnections in socio-technical systems can easily transcend the system and sector boundaries in cities [4]. Avoiding urban lock-ins calls for locally tailored policies that take this interconnectivity into account. Consequently, cities have a growing demand for scientific knowledge to understand the complexity of sustainability transitions and take effective decisions towards urban climate mitigation. Co-creation and decision-support methods in multi-stakeholder engagement spaces have been identified as promising approaches to lead urban climate mitigation [89].

Co-creation can change the modality of urban planners from incremental advances to radical changes that can ensure the success of the mitigation goals. Synthesizing different disciplines from urban, infrastructure, and systems backgrounds into a single inter-disciplinary framework support building a more comprehensive understanding of socio-technical interdependencies in infrastructure systems and thus offers a shared language which can support communication and consensus-building in multi-stakeholder engagement spaces. We contribute to the literature by offering an up-to-date, systems-driven, and accessible categorization of infrastructure interdependency types and interactions which supports the early recognition of these interdependencies and their potential consequences.

Infrastructure interdependencies

In this study, we went beyond earlier studies by utilizing and advancing the proposed infrastructure interdependency frameworks. We investigated social interdependencies that were discussed under different names in a variety of studies, namely Policy/Procedural [28], Market [29], and Culture/Norm (referred as "Societal") [28] by using socio-technical dimensions in the MLP framework [13]. To illustrate, subsidization policies could discriminate infrastructure systems depending on the design of policies. Smartification of the grid leads to a patch of decentralized energy markets on top of the national infrastructure hardware [75]. Interfaces in smart systems can allow exchange of information which can shape users' energy routines and habits. Using the currently V2G systems in smart grids might not be attractive to electric car users if their travel distance are reduced [76]. It becomes increasingly important to identify and emphasize the mechanisms between the different social and technical dimensions of infrastructure interdependencies to better navigate urban transitions.

We discussed two new interdependency types which are heavily influenced by changes over time in socio-technical systems: life-cycle interdependencies [32] and evolutionary interdependencies. Identifying and understanding time-dependent interdependencies calls for a dynamic analysis, an analysis of how the system can change over time [14]. Looking for current-future and future-future interdependencies within this study allowed us to reveal how the time factor could result in different interactions amongst infrastructure systems. There are significant delays and long-term consequences involved in urban sustainability transitions because infrastructure systems have long life-cycles and urban transitions take decades [9]. Consequently, each city will evolve in different path-ways because cities differ in their existing infrastructure systems, their socio-technical context and the resulting co-evolution caused by these differences [43]. Therefore, it can be stated that each city will require a unique master plan that considers the dynamic change in infrastructure systems and their interdependencies. These master plans should strive for providing a comprehensive picture of the interdependencies and their consequences, although the complexity of the issue would surely obstruct these efforts at every level.

Limitations and future research

There was a significant trade-off for this research's design. Building a case study would eventually force a narrower focus and disciplinary research design which would limit the amount of investigated infrastructure systems. Choosing this option would prevent a broader systems analysis and overlook certain influential socio-technical effects. On the other hand, looking at cities as a system of systems calls for a broader focus but then the results are harder to present and it becomes harder to build confidence in these results since the data consists of numerous urban examples and interconnections. That being said, a broad focus can still reveal relevant and influential interdependencies which can motivate more disciplinary and focused future research to shed light on the structures and dynamics of how these interdependencies occur. We have built **Table 1** for exactly that reason: to show the direction for how and where we can look for potential infrastructure interdependencies. A natural next step can be the utilization of this framework in urban decision-making or future sustainability studies.

To achieve that, facilitating co-creation workshops can be a great opportunity [90]. We argue that applying the proposed interdependency framework within multi-stakeholder engagement spaces [89] could identify new opportunities to utilize interdependencies in urban transitions (i.e. by using urban transition labs [4], transition scenarios [90] or group model building [91]. Although we argued that it is virtually impossible to develop or maintain an exhaustive and definite map of interdependencies, researchers and urban decision-makers can still benefit from building proto maps of interdependencies to identify unintended consequences of interdependencies as well as distinguishing cross-sectoral value generation in cities. Utilizing our proposed framework can show this map of interconnectedness and thus help researchers and urban decision-makers to recognize and identify the relevant boundary for research/decisions.

To illustrate, the seven socio-technical dimensions could be used as a starting point to show how infrastructure systems can influence each other, and experts from each socio-technical dimension for that specific project could be invited in a co-creation process to distinguish systemic traps and opportunities in cities.

Furthermore, acknowledging the multi-mode relationships between infrastructures could help researchers or urban decision-makers to "play the devil's advocate" in urban research/decisions. To elaborate, in complex decisions, decision-makers often miss the unexpected consequences of policy actions because they tend to look for mechanisms that would create the intended change and overlook the mechanisms which would obstruct/prevent the intended change. Consequently, using such frameworks can support urban decision-makers and researchers to switch from a linear-focused way of thinking towards a more holistic perspective of systemic interactions in cities. In **Appendix C**, we propose a list of questions, inspired by our framework, to support the co-creation process in cities. Researchers and decision-makers can use the questions and guidelines in **Appendix C** to start mapping infrastructure interdependencies, finding the relevant system boundary and stakeholders for the success of the projects, and support discussions in the co-creation process.

Conclusion

Long-term planning, such as urban sustainability transitions, calls for the consideration of the system's interconnectedness and dynamics, and their effects on the whole socio-technical system to offer robust solutions. Utilizing the understanding of infrastructure interdependencies calls for applying frameworks and methods that allow for crossing disciplinary boundaries. In this paper, we have investigated infrastructure interdependencies with Dutch urban climate-mitigation examples and literature to refine our understanding of their socio-technical characteristics and implications. We presented influential interdependency examples to explain how different multi-modal interactions, infrastructure interdependency types, and urban characteristics can influence the climate-mitigation efforts. We proposed an updated and systemic framework for socio-technical interdependencies in infrastructure systems; thereby, we aimed to support the comprehension of these interdependencies and facilitate the inter-disciplinary communication amongst urban decision-makers via a shared language. A shared language for interdependencies [32] can promote interdisciplinary communication and collaboration in co-creation spaces to tackle the "wicked" complexity at the urban level, allowing a more robust urban decision-making for building sustainable cities.

Appendices

Appendix A - Research data folder

We have created a research data folder along with this paper to discuss the data collection methods and collected data in extent. This folder includes the following files below. Research data folder can be accessed via Mendeley Data on the following link:

Gürsan, Cem; de Gooyert, Vincent (2022), "Infrastructure interdependencies and their implications for urban climate mitigation", Mendeley Data, V6, doi: 10.17632/r95hxbfvb8.6

Methods

1) Document Selection, In Word format.
2) Interview Design, In Word format.

Data Analysis

3) Contextual environment of the Dutch urban sustainability transition, In Word format.
4) Infrastructure interdependencies coding tree, In JPEG picture and PDF format.
5) List of infrastructure Systems from the KlimaatAkkoord, In Excel Table format.
6) List of multi-modal relations between infrastructure systems, In Excel Table format.
7) Infrastructure interdependency matrix, In Excel Table format.

Figures and Tables

8) Figure 1, In JPG and PDF format.
9) Figure 2, In JPG and PDF format.
10) Table 1, In JPG, PDF, Excel format.
11) Table 2, In JPG, PDF, Excel format.
12) Table 3, In Word format.
13) Table 4, In Word format.
14) Table 5, In Word format.

Raw Data

15) Dutch National Climate agreement, In PDF format.
16) City-Zen project, In PDF format.
17) 't Ven project, In PDF format.
18) Merwede project, In PDF format.

Appendix B - Data collection and analysis for the case study

Table 3 - inputs and outputs of data analysis

	Name	Description	File format	Analysis	
inputs	List of Infrastructure Systems from KlimaatAkkoord	Direct quotations were used to identify relevant infrastructure systems for the Dutch urban transition	Excel	35	quotations
	List of multi-mode interactions between infrastructure systems	Citations & Quotations from documents and literature have been used to show multi-mode relationships between infrastructure systems	Excel	440	quotations
outputs	Infrastructure Interdependency Matrix	This matrix presents the multi-modal relationships that were found during the analysis.	Excel	300	interdependent relationships
				489	multi-mode relationships
	Overview of Dutch urban transition	More explanation on the context of the Dutch urban sustainability transition	Word	2	page summary

Table 4 - Reviewed documents for the case study

Name	Reviewed document	Description	Organization	Date	Document	Pages
Klimaatakkoord	Climate Agreement	National Climate Agreement of the Netherlands, presented to the House of Representatives on the 28th of June, 2019.	Dutch Parliament	28/Jun/19	National agreement	247
'T Ven	Uitvoeringplan aardgasvrije wijk 't Ven	District heating network implementation plan for the 't Ven neighborhood.	Eindhoven Municipality	29/Jun/18	Project plan	47
CityZen	CityZen - A balanced approach to the city of the future	Results report for the smart grid system in Amsterdam area for the EU funded CityZen project.	CityZen Consortium with 28 partners	Dec/19	Results report	147
Merwede	Stedenbouwkundig Plan	Urban plan for redeveloping the Merwede as an integrated residential neighborhood.	Utrecht Municipality	06/Nov/20	Urban plan	186

Table 5 - Conducted interviews

Responsibility	Organization Type	Contributed Information
Mobility expert	Municipality	How municipalities make decisions on sustainable mobility and future challenges of cities in the Netherlands
Transition Lobbyist	Housing Association Consortium	How municipalities collaborate with housing associations to drive the transition out of natural gas in the built environment. Lobbying and decision making activities to accelerate the urban heating transition
Climate Adaptation	Municipality	How municipalities deal with the challenges regarding the climate adaptation and water management. How other infrastructure systems could affect the climate adaptation efforts
Portfolio and risk	Energy Services Main Distributor	How the renewable electricity generation could impact the carbon-neutrality efforts in the Netherlands
Project Manager	Energy Services Main Distributor	What are the cross-cutting innovations in renewable integration and battery technologies in the Netherlands and how could these affect the carbon-neutrality efforts in the future
Innovation consultant	Institute for Sustainability	How does the innovation process works in different technologies in the Netherlands? What are the steps for a successful innovation of energy systems?
Strategic hydrogen advisor and researcher	Academy	How could hydrogen be used to replace fossils in electricity and heat generation in the Netherlands and Europe. What are the cross-cutting technologies available in the world. What are the challenges against mass-scale adoption of hydrogen
Sustainability transition researcher and advisor	Institute for Sustainability & Academy	How are climate strategies in the Netherlands made? What is the current policy-making environment overlook or does well? What are the social implications of current climate strategies and how can we overcome systemic traps?
Hydrogen Advisor	Institute for Sustainability	How could hydrogen be used to replace fossils in electricity and heat generation in the Netherlands and Europe. How are climate strategies in the Netherlands made? What is the current policy-making environment overlook or does well? What can be done to improve the climate strategies
Climate researcher	Academy	What are the current biomass and biogas technologies available in the Netherlands. What are the barriers and opportunities for these technologies in the future?

Appendix C - Questions for co-creation processes inspired by the framework

a) **Socio-technical dimensions**

a. Functional interdependency

- What is the function of the current infrastructure system? What is the function of proposed infrastructure system?
- How do the current infrastructure system influence other infrastructure systems due to its functions (e.g. material input-output, supply-demand, informational input-outputs, etc.)? How do the proposed infrastructure system influence other infrastructure systems due to its functions?
- Depending on the answer to the last bulletpoint: What are the main changes if we stop using the current infrastructure system and switch to the proposed infrastructure system? What services will be enabled/ hindered due to this change?
- Which stakeholders/actors know more about these functions? How can we include these stakeholders and actors in the decision-making/ research process?

b. Evolutionary interdependency

- What are the predominant evolutionary characteristics for the city in question, current infrastructure system, and proposed infrastructure system?
- How can the ongoing innovations, evolutions, technological trajectory affect the city in question, current infrastructure system, and proposed infrastructure system?
- Which stakeholders/actors know more about this evolutionary trajectory? How can we include these stakeholders and actors in the decision-making/ research process?

c. Spatial interdependency

- What are the predominant spatial characteristics for the city in question, current infrastructure system, and proposed infrastructure system?
- How can these spatial characteristics affect the city in question, current infrastructure system, and proposed infrastructure system?
- Which stakeholders/actors know more about this spatial characteristic? How can we include these stakeholders and actors in the decision-making/ research process?

d. Life-cycle interdependency

- Are there any ongoing contracts for existing infrastructure systems? What are the durations for these ongoing contracts?
- At which life-cycle stage is the current infrastructure system? How long does the current infrastructure system has until the city needs a new infrastructure solution?
- Do we need long-term contracts for the proposed infrastructure system? What should the contract durations be for the proposed infrastructure system? Is the proposed infrastructure system a bridging solution or a destination solution [14]?
  - If it is a bridging solution, do the long-term contracts have conflicts with destination solutions in the future?
- At which life-cycle stage is the proposed infrastructure system? Do we have enough time to develop this system in regards to the life cycle stage of the current infrastructure system?
- Which stakeholders/actors know more about the life-cycle stages/contract durations and qualities for the current and proposed infrastructure systems? How can we include these stakeholders and actors in the decision-making/research process?

e. Policy/Procedural interdependency

- How do the existing policies/regulations/procedures affect the current and proposed infrastructure system?
- Are the national/city level policies/regulations/procedures consistent with each other? Do all of the policies align to bring the same intended outcome? If not, what could be repercussions between inconsistencies in policy instruments? [92]
- Which stakeholders/actors know more about the policy instruments that affect current and proposed infrastructure systems? How can we include these stakeholders and actors in the decision-making/research process?

f. Market interdependency

- How can the market configuration of the current infrastructure system and the market configuration of the proposed infrastructure system influence each other?
- Do the market configuration of the current infrastructure system have enabling/obstructing effects on the proposed infrastructure system?
  - If so, what are these effects?

  - o How can we negate the negative influence on the proposed infrastructure system?
  - o How can we enable the positive influence on market configurations of the current and proposed infrastructure systems? How can we include these stakeholders and actors in the decision-making/research process?
- Which stakeholders/actors know more about the market configurations of the current and proposed infrastructure systems? How can we include these stakeholders and actors in the decision-making/research process?

g. Culture/Norm interdependency

- What are the predominant culture/norm characteristics in the city regarding the use of infrastructure service?
- How does the current infrastructure service satisfy or conform the city's/neighborhood's culture/norm regarding the infrastructure service?
- Can the proposed infrastructure system satisfy or conform the city's/neighborhood's culture/norm regarding the infrastructure service in the same way?
  - o If not, how does the proposed infrastructure system satisfy/conform the culture/norm differently? What could be the repercussions of such a change?
- Which stakeholders/actors know more about the culture/norm in city/neighborhood regarding that infrastructure service? How can we include these stakeholders and actors in the decision-making/research process?

h. Cross-sectoral interdependencies between dimensions

- Could any of the mentioned interdependencies above influence other sectors? (e.g. a policy interdependency between two systems changes the market configuration and pricing of infrastructure services)
- Did we include all of the necessary stakeholders/actors to reveal such cross-sectoral effects? If so, can we provide a co-creation environment to make coherent and consistent decisions? If not, how can we know more on who to include and how can we persuade them to join the co-creation process?

b) **Multi-mode relationships**

- What are the intended change in the current infrastructure system and the proposed infrastructure system?
  - o What are the mechanisms that can lead to the intended change in the current infrastructure system? What are the mechanisms that can lead to the intended change in the proposed infrastructure system?
  - o How can we activate these mechanisms? What are the policy instruments that can reinforce these mechanisms?
- What are the unwanted change in the current infrastructure system and the proposed infrastructure system?
  - o What are the mechanisms that can lead to unexpected change in the current infrastructure system? What are the mechanisms that can lead to unexpected change in the proposed infrastructure system?
  - o How can we prevent these mechanisms from occurring? What are the policy actions and instruments that can lead to these unexpected/unintended consequences?
- Are these any way that the current policy instruments and climate actions could lead to desired/unintended outcomes when we think of these policies acting on the whole system simultaneously?
  - o What are the inconsistent policy instruments?
  - o How can we align these policy instruments?

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Chapter 3

The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition?

This research has been inspired by Cem Gürsan's master's thesis from 2019, which was supervised by Dr. Vincent de Gooyert. The work-in-progress research paper was presented at the 38th Annual International Conference of the System Dynamics Society in Bergen - Norway in 2020. The article was published at the Renewable and Sustainable Energy Reviews journal in 2021 and was co-authored by Dr. Vincent de Gooyert. The feedback analysis done in this research have been well-received by scholars and policymakers, as this article received more than 160 academic citations and 10 policy citations from organizations such as International Monetary Fund and United Nations by 2024.

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Abstract

In the Paris Agreement, many nations set ambitious global goals to stabilize and reduce carbon emissions to mitigate climate change. A large share of these emissions is caused by electricity production. Scientists have been debating the viability of using natural gas as a transition fuel while renewable energies mature technologically and economically. Although natural gas might help the energy transition by reducing emissions compared to coal, there are other long-term implications of investing in natural gas which can work against reaching climate goals. One concern is that investments in natural gas might crowd out investments in renewable alternatives.

This research reviews the literature on the role of natural gas in reducing carbon emissions to mitigate climate change and to bridge between coal and renewable technologies. We advance the debate by laying out how various positive and negative effects of natural gas interrelate. Our research warns that natural gas' negative delayed and global effects can easily outweigh the positive immediate and local effects unless precautions are taken.

Existing studies agree that natural gas helps avoid greenhouse gas emissions in the short term, while unintended long term effects might also hinder the transition into renewables. Our review helps to inform the policy-making process by reviewing the systemic effects of using natural gas as a transition fuel and suggests policy actions to avoid the negative long term consequences.

Keywords
Natural Gas, Energy Transition, Carbon lock-in, Fossil Spillover,
Energy Rebound, System dynamics

Introduction

Natural gas, due to having approximately half the CO_2 polluting effects vis-à-vis other fossil fuels [1,2], has been considered as a transition fuel before renewable energy's technological viability can surpass its challenges to produce secure and sustained energy [1]. Transition fuel in this context means: a substitute low-carbon fuel (natural gas) for higher content fossil fuels (coal and oil) to reduce CO_2 emissions in the near future [3]. Natural gas' role of bridging between more polluting fossil fuels and zero-carbon technologies is considered only as a temporary role because natural gas still emits CO_2 emissions [2,4]. The uncertainties and complexity of the issue divide stakeholders (policy-makers, scientific community, NGOs, and public) into conflicting factions. One view argues that natural gas can help with the current challenges of renewables [1,5,6]. However, others oppose this view by warning that natural gas might create a continued dependency on fossil fuels [7–9]. On one hand, natural gas can synergize with renewable technologies to balance intermittent electricity outputs [6,10,11] and provide uninterrupted energy even during peak hours [7,10,12] with their flexible on-off cycles [6,7,13]. On the other hand, investing in natural gas infrastructure might delay the transition to zero-carbon technologies and hinder the emission mitigation efforts in the long-term [9,12,14].

The recent IPCC report and Paris Agreement [15,16] stress the importance of implementing appropriate climate policies promptly. To design appropriate policies, more knowledge is needed on the *global* and *long-term* effects of using natural gas as a transition fuel. The objective of our study is to provide such knowledge through analyzing existing studies on the potential of natural gas as a transition fuel. We derive conclusions by looking for commonalities and differences between the reviewed papers and advance the debate by laying out how various positive and negative effects of natural gas interrelate. The research question is: what are the effects of using natural gas as a transition fuel in terms of helping or hindering the energy transition? Our research suggests that overlooking natural gas' negative delayed and global effects can outweigh the positive immediate and local effects, unless appropriate policy measures are taken.

Theoretical background

The energy transition

In the context of this paper, we refer to energy transition as the transition towards environmentally and economically sustainable energy technologies which help the world to mitigate climate change. The Paris Agreement set out a long-term vision to create a climate-neutral economy by 2050 [16]. The nations in the Paris Agreement would like to lead the way to climate-neutrality by synergizing policies for industry, finance, and research, funding feasible and achievable technology options, and empowering communities [16]. Although the nations of the world had also set ambitious global goals during the Kyoto Protocol [17], CO_2 emissions have continued to increase as shown in **Figure 1** [18,19]. In May 2019, CO_2 emissions have reached a critical level of 414 ppm, a mere sprint away from the global goal of staying under 450 ppm [19,20]. More than 40% of the CO_2 emissons is caused by the electricity and heat sector as shown in **Figure 2** [21,22].

One possible reason for the continued emissions resides in the *global scale* of the goals. Nations differ in the extent that they have access to technology and resources which affects the pace of each nation's transition. However, the extent to which the Paris goals are met depends on global emissions. Therefore, it is worthwhile to investigate the *global effects* of investments in natural gas as a transition fuel instead of considering only the local effects. Investments that seem rational on a local level can have unexpected and undesired global outcomes.

Another challenge for emission mitigation is that the effects of climate change present themselves in the *long-term*. There is a substantial delay between emissions and their impact on the global climate because emissions accumulate progressively over time. Even if every coal and oil plant was shut down today, CO_2 in the atmosphere would not dissolve immediately but would do so with a time delay [23]. Similarly, the goal of a climate-neutral economy has a long-term horizon. The current infrastructure is based on fossil fuels and the pace of transitioning away from fossil fuels substantially impacts the associated costs of writing off existing infrastructure. Because of the long-time horizon of the climate change and energy transition, it is worthwhile to analyze the impact of investments in natural gas on the *long-term*.

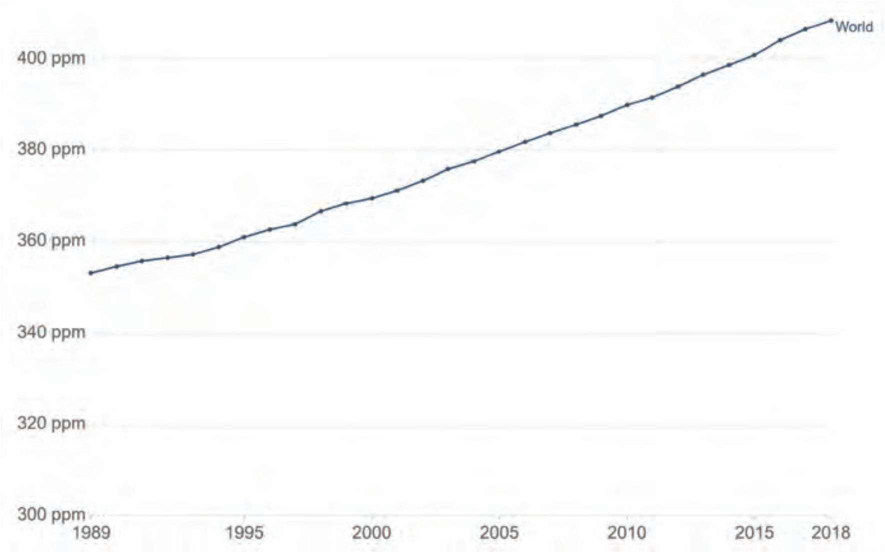


Figure 1 - Current trend in the CO_2 concentration has not changed after the Kyoto protocol in 1997 [18].

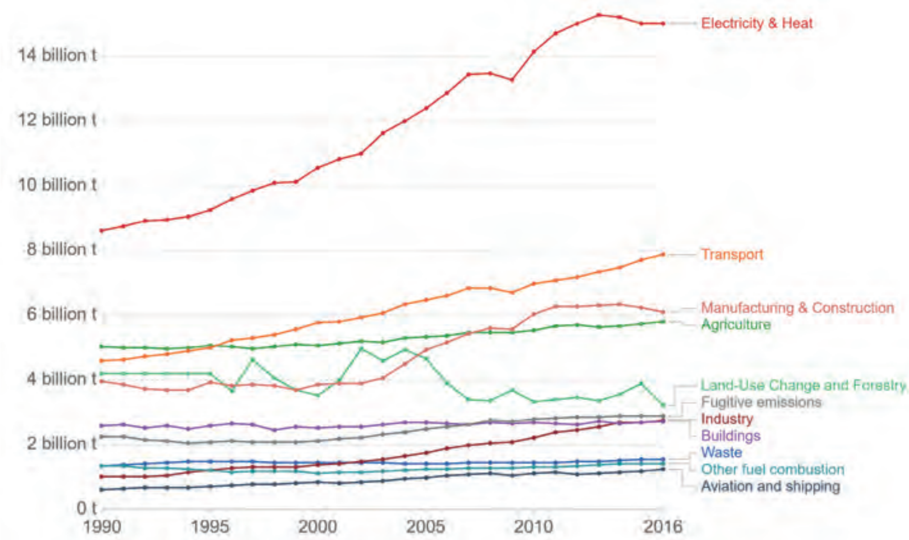


Figure 2 - Tons ofgreenhouse gas emissions by sectors [22].

A systems approach

Climate change, being a global and long-term problem [24], is a suitable object to be studied using a *systems approach*, a scientific tradition that puts exactly these characteristics central stage [24–26]. An important characteristic of the systems approach, compared to approaches that pay more attention to local and immediate effects, is that circular-causality is considered. Systems approaches focus on how interconnected elements affect each other and through these other elements themselves again over time [24–26], aspects that typically are beyond the scope of other approaches. We define a *system* as interconnected elements which are organized in a certain way [24]. Systems approaches focus on the interdependence of elements [26], and the many two-way interdependencies in systems lead to *feedback* effects.We will illustrate two different types of feedback effects with examples. **Figure 3** shows a reinforcing feedback effect. Natural gas power plants need various infrastructure investments which consist of pipelines, fuel processing facilities, and storage. When the pipeline infrastructure exists, several gas plants can benefit from it. If pipelines are not present, natural gas has to be processed into transportable forms such as LNG. Installing pipelines reduces the transportation costs for future natural gas plant investments. In turn, gas plants become more attractive to invest in. Moreover, installing natural gas plants would make it more attractive to invest in natural gas infrastructure for reducing costs. In this type of feedback, the elements are reinforcing each other because an initial increase in one of the variables leads to a further increase of that same variable through the other variables. The opposite also holds: an initial decrease of one of the variables leads to a further decrease of that same variable through the other variables.

Figure 4 shows a balancing feedback effect. In this type of feedback, the elements in the feedback loop affect each other until a goal is reached. An initial increase of a variable leads to a decrease of that same variable, through the other variables. This effect continues until the system is in equilibrium. To illustrate, the relationship between the energy gap and power plants can be considered. An energy gap occurs when the energy demand cannot be met with current capacities. To provide uninterrupted energy, new investments are required. Installing power plants will satisfy the energy gap. In this type of feedback, the elements cease to change their levels when the goal is reached. These feedbacks are called balancing feedbacks since they have a stabilizing effect on the system.

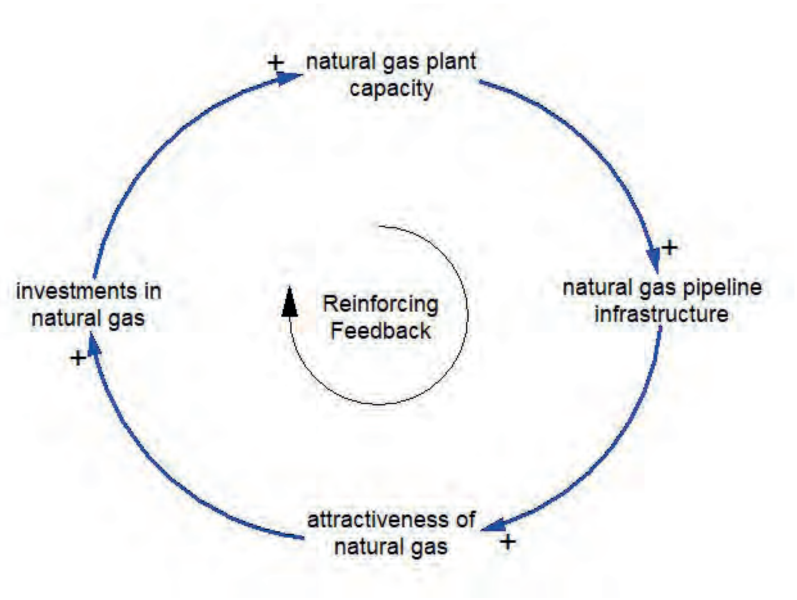


Figure 3 - Reinforcing Feedback Example – The relation between pipeline infrastructure and installed natural gas capacity.

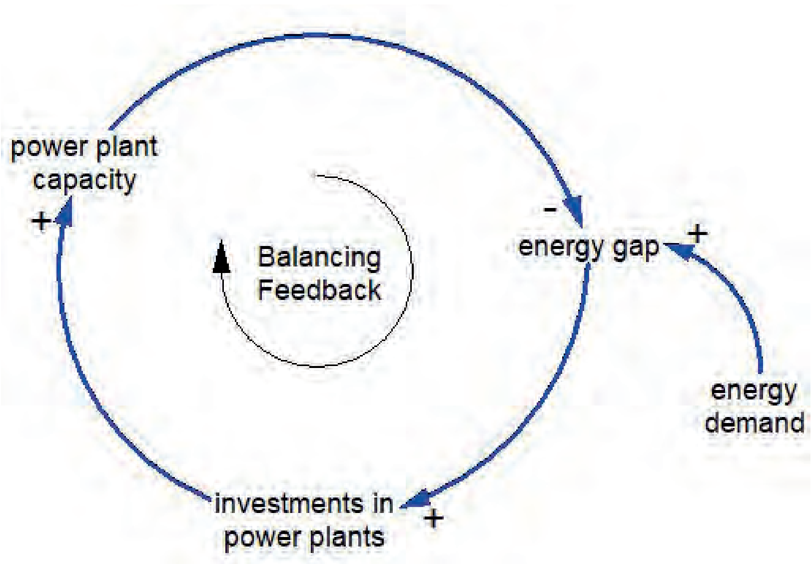


Figure 4 - Balancing Feedback Example – The relation between the energy gap and installed power plant capacity.

Feedbacks can form resilient structures, bring unexpected outcomes, and become insensitive to policies [27]. Overlooking the interdependencies in policies can create more problems than solutions [28]. The systems approaches complement other approaches by studying interdependencies, allowing synthesizing insights that have been gained through more disciplinary approaches. System dynamics (SD) is one of the systems approaches that is characterized by utilizing modeling techniques [24,25]. SD has been applied to the electricity generation and energy transition [27,29,30]. SD models can conjoin various theories and views on a debate and provide a tool to discuss their dynamics [31,32]. Thus, this research aims to complement existing studies on the natural gas debate by applying SD modeling.

Direct and indirect effects of natural gas as a transition fuel

In the context of this study, we classify local, immediate, short-term[1], and linear effects as *direct effects*. We classify global, delayed, long-term[2], nonlinear, and feedback effects as *indirect effects*. To elaborate on the differences between direct and indirect effects, we summarize the advantages and drawbacks of using natural gas in the energy transition.

Natural gas can assist renewable technologies and replace more polluting fossil fuels. Renewable wind and solar technologies provide intermittent energy [10,11,33]. These renewable technologies are dependent on the renewable resource availability that nature provides. For example, solar panels can only generate electricity when exposed to an adequate amount of solar rays. A solution to this problem might be found in storing energy (via sustainable energy carriers) and electricity grid innovations. However, these solutions are currently not always commercially, technologically, or environmentally viable (see studies [6,12,34,35] mentioning these various challenges). Another challenge is the renewables' high costs. Natural gas stands out as a transition fuel because of its economic viability compared to emerging renewable technologies and less polluting effects compared to other fossil fuels (see studies [5,6,33,34] mentioning advantages of natural gas). Overall, natural gas can *directly* affect the energy transition positively by helping renewables by providing uninterrupted energy and reducing emissions by replacing coal [6,34].

Figure 5 shows the electricity production by fuel source. In 2014, 41.1% of the global electricity was produced by coal, 21.92% was produced by natural gas, and only 6.1% was produced by renewables (exluding hydropower) [36]. If natural gas can redirect investments from coal, it would have a significant growth potential. While natural gas is replacing coal, this transition would reduce the annual emissions. Sequentially, zero-carbon technologies can replace natural gas until climate-neutrality is achieved.

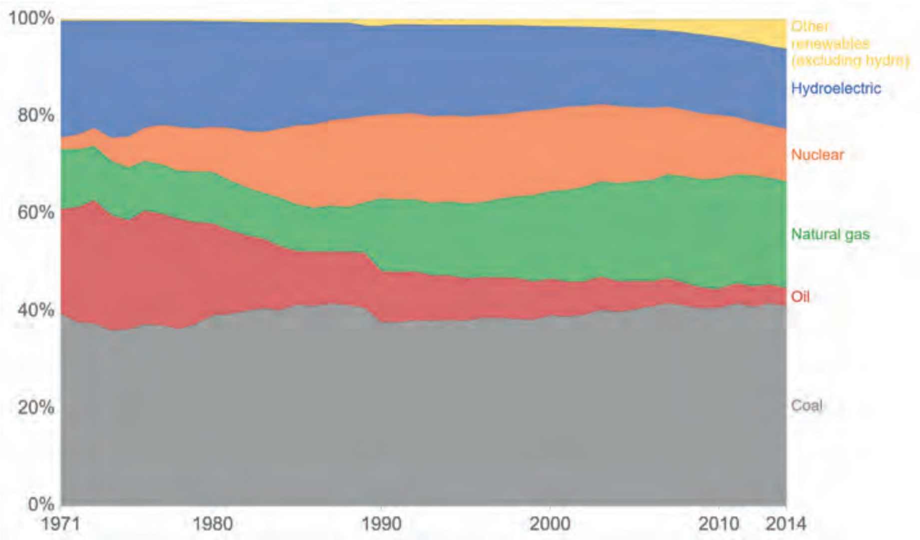


Figure 5 - Electricity production share by fuel source in 2014 [36].

That being said, investing in natural gas is controversial because of its environmental uncertainties and potential future repercussions. One of the notable *indirect effects* of natural gas is the crowd-out effect mentioned by several authors [7,9,12,14,33,37–40]. Crowd-out happens when a bridging technology (natural gas) siphons investments from an emerging technology (renewables). Through crowd-out, investments in natural gas may lead to continued investments in other fossil fuels, because of the accompanying reinforcement of the fossil fuel infrastructure, and diminish investments in renewables [9,38]. Direct environmental benefits of gas can be nullified if it indirectly leads to a prolonging of the fossil fuel infrastructure. The role of natural gas as a transition fuel can fail if gas supports other fossil fuels instead of replacing them. To advance the debate on natural gas as a transition fuel, therefore, we investigate its systemic effects on the energy transition. We contribute to the literature by discussing the interrelated indirect effects of natural gas.

Methodology

Our study investigates indirect effects of using natural gas as a transition fuel. To this end, we carry out a systematic literature review. We used secondary data from papers, books, and reports from academic and industrial sources. For the data analysis, we first utilized open and axial codes in the selected literature to expose the debate in detail and discover causal relations regarding the effects of gas. Then, qualitative stock and flow diagrams (SFD) [25] were built using the coded material. In the following subsections, we discuss these various steps in more detail.

Open and axial coding to build models

Debates can be clarified by comparing conflicting views about the problem and its solution [41]. This type of comparative thinking approach can help us verify the validity of current hypotheses and reveal new insights about the debate [41]. Thus, we carried out a systematic literature review on the debate of *natural gas as a transition fuel*. Coded and structured secondary data can form an empirical foundation to build theoretical models where ongoing scientific theories and views can be explored with clarity [42]. A disciplined qualitative description of a system can identify systemic forces such as feedback loops and delays to generate insights and explain a complex narrative in a single diagram that normally requires many pages [43]. Thus, we aimed to build qualitative theoretical models from coding to reveal new implications by synthesizing different views [31,42].

Coding practices for building models have a four-step approach [44]. The first two steps contain a mixture of open and axial coding to structure the data and debate [44–47]. In the first step [44–47], we used open codes with an inductive approach to identify relevant and recurring themes in the debate. Then, we utilized axial codes to categorize these views into a hierarchical coding tree [44][3]. By reiterating through axial codes, we structured and formatted revealed patterns in data to corroborate the opposing views in the debate [48]. As a result, the coding tree captured various effects of gas into subgroups according to the documents' interests and claims. From the coding tree, **Table 1** was built showing natural gas' direct and indirect effects as well as the positive/uncertain/negative nature of the effect. The last two steps are *identifying the causal relationships* and *representing the model* [44]. These two steps are completed in the results section through the presentation of SD models [44].

Stock and Flow Diagrams

System dynamics diagrams can represent how different variables of a system are interconnected in feedback structures [49]. They denote the connection between elements that are responsible for system behavior [50]. The causal links connect the variables in SD diagrams. The nature of the links is explained by different annotations on causal arrows [50]. A **+** sign on an arrow means that the connected variables change in the same direction. Whereas a **-** sign means that the connected variables change in the opposite direction. The delay sign, **II**, means that the causal effect does not happen instantaneously but with a time delay. Feedback loops are formed through closed chains of causal relations. Reinforcing feedback loops are presented with an **R** letter and balancing feedback loops are presented with a **B** letter.

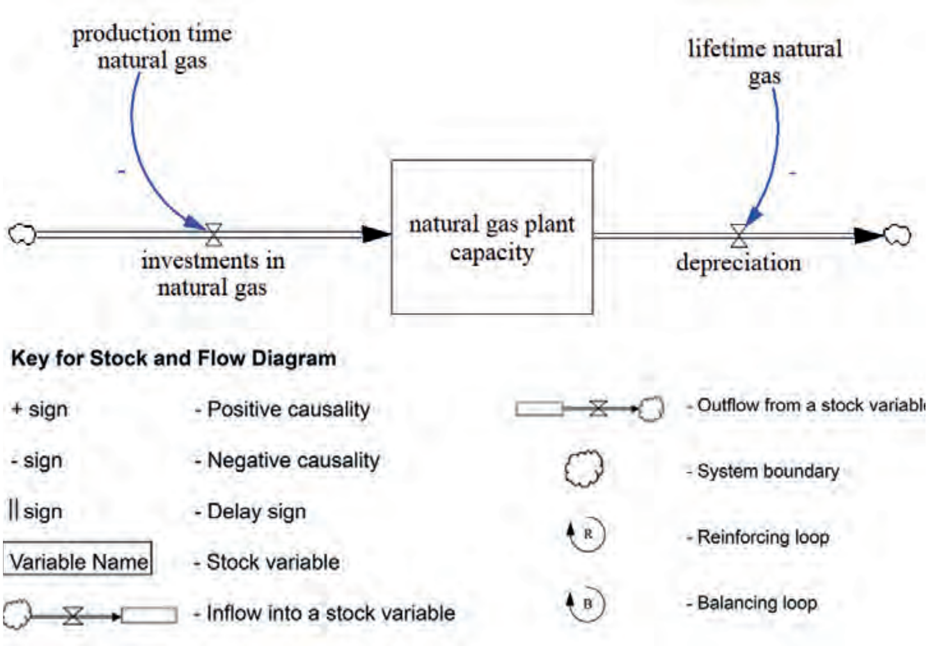


Figure 6 - SFD example.

System dynamics has two main types of diagramming approaches: Causal Loop Diagrams (CLD) and Stock and Flow Diagrams (SFD). **Figures 3** and **4** are CLD representations of various feedback loops. CLDs are appropriate when the aim is understanding and visualizing the feedback structure of a system. CLDs can help us model complex systems in an accessible way [50]. However, CLDs become ambiguous when aggregating certain variables and structures for the sake of simplicity [50]. SFDs can overcome CLDs' ambiguity because they differentiate between stocks and flows. Stocks are state variables [25]. They represent the variables in the system which accumulate or deplete over time and thus have a certain level (or state) at a given time. Flows are the rates that alter the stocks [25].

In the scope of this research, natural gas plant capacity is a stock. Investments in natural gas is an example of an inflow and depreciation of natural gas is an example of an outflow. When an investment decision is made, it typically takes two to three years to build a natural gas plant [51] and a gas plant's economic lifetime is approximately

30 years [52]. Therefore, changes in stocks are not instantaneous but rather they happen over time through connected flows as shown in **Figure 6**. Distinguishing stocks and flows provides a better operational representation of the system [25]. SFDs also provide a starting point for quantification in future research [50]. For these reasons, we have chosen to use SFDs.

Systematic literature review

We built our models using secondary data: documents consisting of academic or expert books, reports, and papers. We used Scopus, Web of Science, ScienceDirect, and Google Scholar databases to access the documents. Searching "Natural gas", "clean energy" and "transition fuel" as keywords returned 585 results. In this research, solar and wind energy technologies have been chosen as renewable energy technologies and coal has been chosen as the competing fossil fuel. **Appendix A** contains more information on selection and filtering. **Figure 7** shows a summary of the filtering steps.

15/06/2020 Databases
Scopus ScienceDirect WebOfScience Google Scholar
Keywords
"Natural Gas" AND "Clean Energy" AND "Transition Fuel"
Search Results
585

Filtered-out	
Law, Foreign Affairs, Chemistry, Mechanical Engineering	83
Shale, Fracking	218
CNG,LPG,LNG	75
Hydrogen	79
Energy in Other Sectors (Transportation, Heating, Household, etc.)	27
Focus on other fuels or technologies	17
Not focused on Transition	9
No dynamics between natural gas and renewables	3
Natural gas as a peripheral topic, off-topic	25
Redundant Papers in databases	7
Remaining	42

Figure 7 - Filtering steps used in the literature.

Results

Table 1 presents the classification of mechanisms that resulted from our review of the literature on natural gas as a transition fuel. We looked for commonalities and differences across studies in reiterations that in the end converged in five themes that recurred in the literature. These four main themes are: Energy Reliability, Sociotechnical effects, Energy Costs, and Environmental Impact3. There are twelve sub-themes as shown in Table 1 and coding tree in Appendix B. In Table 1, we show that many authors mention the positive direct effects of natural gas for the energy transition. Natural gas can immediately help renewable technologies with their challenges through various mechanisms. The reviewed studies converge on the idea that natural gas can help with the energy transition with its positive direct effects. However, Table 1 also shows that the issue becomes complicated when indirect effects are considered. The studies diverge on the indirect effects of natural gas, with some mentioning positive, and many mentioning negative and uncertain effects under three main themes: sociotechnical effects, environmental impacts, and energy costs. Below we discuss each of these themes in more detail, which will form the foundation to then discuss the various factors that will determine the occurrence of positive and negative effects. Finally, we will utilize qualitative SFD models to create a comprehensive view of the indirect effects of gas as a transition fuel.

Energy reliability

Many studies mention natural gas' potential role in the provision of secure and reliable energy. We distinguished three sub-categories under the energy reliability theme: intermittency, flexibility, and peak demand. *Intermittency* refers to renewables' characteristic of providing variable energy outputs. Wind and solar power produce energy when there is resource availability[4]. Generated but unused renewable energy cannot be utilized unless they are stored or transported. Furthermore, abrupt fluctuations in resource availability directly affect electricity generation output throughout the day. This makes it even harder to anticipate the electricity generation potential, to ensure the grids' stability, and thus to satisfy electricity demand reliably. Natural gas plants, however, can be leveled to an energy demand if needed. Thermal plants can reduce their electricity generation levels to secure the grids' stability when energy demand drops. Hence, natural gas plants can accompany renewable plants to balance the intermittent electricity generation (see studies [2,6,7,10,11] mentioning natural gas' help with intermittency).

Table 1 - Table of Literature Comparison and Categorization

Themes	***Positive direct effects***	***Positive indirect effects***
Energy reliability		
Intermittency	[2,6,57–60,7,10,12,14,53–56]	-
Flexibility	[2,6,58,60,61,7,10,13,14,33,53–55]	-
Peak demand	[1,10,12–14,40,55,58,62,63]	-
Sociotechnical Effects		
Crowd-out Effect	-	[6,40,57,63–65]
Carbon lock-in	-	-
Energy rebound	-	-
Environmental impact		
CO_2 emissions	[1,5,55–57,59,61,64,66,68,69,6,7,10,12,13,33,40,54]	[70]
Other emissions	[1,6,33,57]	[72]
Replacing coal	[1,5,57–62,64–67,6,12–14,33,40,54,56]	[6,64,67]
Other environmental effects	[1]	-
Energy costs		
Transition costs	[1,6,10,33,55–57]	-
Electricity generation costs	[1,5,61,62,66,6,10,13,33,54,56,57,59]	[33]

Flexibility refers to the ability of swiftly increasing and decreasing energy production at will. As discussed, renewable energy plants' total electricity generation capacity is limited to the availability of renewable resources. When the energy demand exceeds resource availability, renewable plants cannot provide electricity even if the plant capacity is more than sufficient. To prevent blackouts and brownouts, the resulting energy gaps have to be satisfied. Natural gas can assist renewable plants in compensating such energy gaps because of its flexibility. Natural gas plants have short on-off cycles and thus compensate renewables' fluctuating differences between electricity supply and demand. If renewable power plants cannot satisfy the energy demand, gas plants can be switched on to secure continuous energy. If renewable energy plants can satisfy the energy demand, then gas plants can be turned off easily to minimize resulting emissions from burning gas (see studies [6,7,10,13] mentioning natural gas' flexibility).

Peak demand refers to the ability of providing sufficient energy even when energy consumption fluctuates at higher levels during specific time periods of the day. For example, energy demand would be higher during hot summer noons due to

Negative indirect effects	*Uncertain indirect effects*
-	-
-	-
-	-
[7,9,56,65,66,12,14,33,37,39,40,54,55]	[7,8,13,14,33,53,65–67]
[7,9,11,12,57]	[9,11,12,38]
[13,67,68]	[67]
[1,12,39,54,57,66,68,71]	[7,13,33,54,57,66,67]
[1,12,71–73,13,40,54,57,59,62,67,68]	[1,33,57,59,62,67,72]
[12,13,37,71]	[7,37,54,62,66]
[1,12,13,33,39,40,59,67]	[1,40]
[6,7,11,12,33,56,57]	[7]
[12,13,52]	[40,59]

an increased air conditioning and refrigeration load, or in a cold winter night due to an increased heating load. Uncertainties in peak demands force the investors to overbuild capacity [74]. Renewable technologies need to be compensated by higher levels of overcapacities due to their dependence on resource availability. These overbuilt capacities lay dormant when there is no peak demand [74]. Providing continuous energy to the grid becomes harder when trying to satisfy the uncertain peak demands with uncertain renewable resource availability. In this endeavor, natural gas can help relatively inflexible renewable technologies to provide secure and reliable energy. To reduce the level of overcapacity in the electricity supply, natural gas "peaking" plants can complement renewable plants (see studies [10,14,40,63] mentioning natural gas' peaking potential).

At this moment, natural gas is one[5] of the viable options to address renewable energies' intermittency by providing secure and reliable energy even at peak demands with their flexible on-off cycles. **Table 1** shows that authors only mentioned direct positive effects for this theme. Renewable technologies require help from other technologies to provide reliable energy. According to our review, natural gas can assist in all of the sub-categories. There were no negative or uncertain effects mentioned in the literature for this theme.

Sociotechnical effects

This theme investigates the effects caused by the dynamics between gas' social and technical components. There are three sub-themes under this theme: crowd-out effect, carbon lock-in, and energy rebound. *Crowd-out* can be defined as a constant redirection of investments from a desired technology due to the attractiveness of another technology. Crowd-out occurs when different types of energy technologies compete for investment. An incumbent technology can dominate the market and prevent alternative technologies to emerge [9]. This theme investigates whether the natural gas siphons investments from renewables systemically as mentioned by several authors [7–9,33,38] or supports renewables as mentioned by others [40,57,63–65]. The responsibility of natural gas as a transition fuel is well-defined in the literature: synergize with renewable technologies *until* they become a viable option to provide affordable and reliable energy [33,63]. This synergy between gas and renewables can smooth-out the transition's burden on the society and energy configuration. However, crowd-out can also occur as a result of both technological evolutions and social mechanisms (adoption of users, inertia of institutional design, etc.) of natural gas. If natural gas constantly redirects resources because of its increasing sociotechnical power, then it might crowd-out renewables and reinforce a lock-in to fossil technologies.

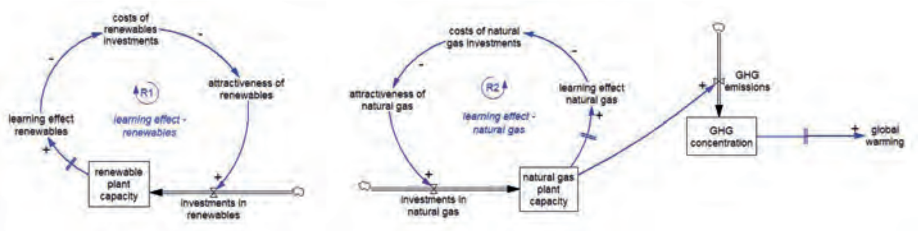


Figure 8 - SFD representation for the learning effect feedback.

Carbon lock-in constitutes the dependency on fossil fuel technology pathways as a result of the crowd-out effect. Existing infrastructures dependent on fossil fuels can hinder advances in emerging renewable technologies [9,38] and this results in the continuity of fossil fuel infrastructures and technologies despite the environmental consequences [9]. Carbon lock-in can create a barrier for renewables and prolong the transition into new designs which can settle the existing environmental disputes [9]. Therefore, energy systems might be locked in on a fossil fuel path if the crowd-out effect is prolonged.

Table 1 shows that some authors [40,57,63–65] mention positive indirect crowd-out effects. Some [9,57,64] argue that natural gas will help renewable technologies with positive direct effects and renewable technologies will ultimately become economically and technologically viable. Channel et al. [40] discuss that renewables and natural gas are not in direct competition since natural gas can be used for other purposes (fuel alternatives for heating and transportation). Parkinson [63] mentions that natural gas will be used as a leverage to fill in the gaps of renewable technologies and will soon be priced out of the conventional market. Then, emerging renewable technologies will become incumbent as long as natural gas is used as a leverage to enable renewables. Most of these arguments rely on technological learning [75]. Technological learning refers to the decrease in a technology's unit costs as the experience in the manufacturing process increases [75]. As the experience on a technology increases with time, unit costs for that technology drops. **Figure 8** shows how directed investments towards renewables can activate the learning effect feedback (R1) and decrease their costs so that renewables become more attractive[6].

Yet, some authors [7,9,12,14,33,38–40] argue that natural gas would divert investments from renewable technologies by causing a crowd-out effect and eventually result in a carbon lock-in unless specific policies are present. The learning feedback applies to any type of technology. If natural gas is chosen for its affordability and ample supplies, this would make natural gas even more economically viable and technologically mature in the future. The physical and informational networks of natural gas and other fossil fuels can become more valuable as the users grow in size [9]. This value is multiplied as many sub-systems of natural gas evolve with fossil fuels' primary network [9]. Every time renewables are not chosen, their relative position against natural gas and other fossil fuels declines because they would be lacking the required network and infrastructure to expand their reach [9]. To conclude, every energy source competes with each other to satisfy energy demand. If one technology becomes attractive, its advantage can be reinforced through the learning feedback. **Figure 9** shows an SFD representation of the competition to satisfy the energy gap.

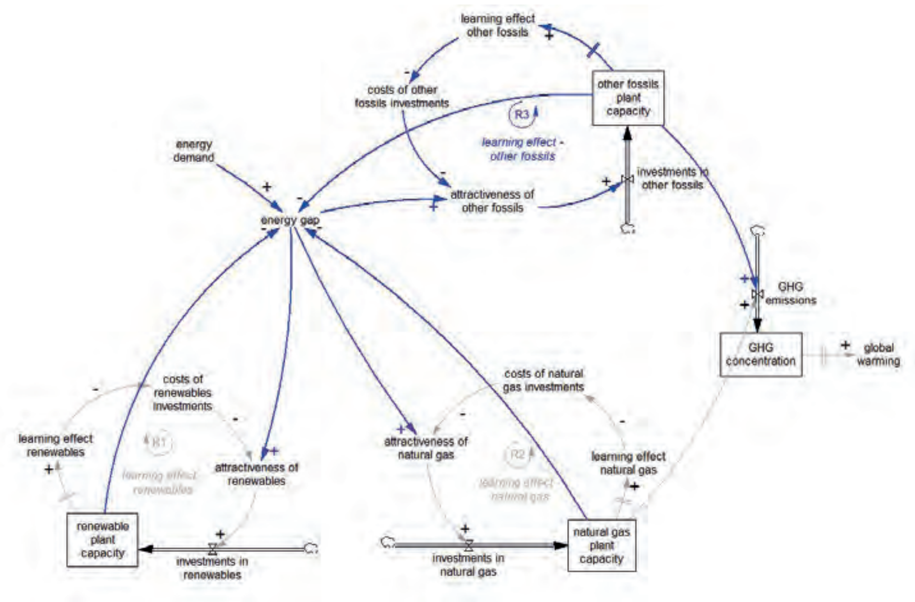


Figure 9 - SFD representation of the energy source competition to satisfy energy demand.

The success of attaining clean energy systems depends on how well policy efforts are handled (see studies [2,6,7,13,64] mentioning the policy necessity). Baron et al. [7] explain several policies to enable renewable technologies. Reforming energy subsidizations is the first discussed policy. Renewables can be subsidized to increase their viability. Renewable subsidies are intended to increase the shares of renewables in the fuel mix. Although these subsidies would increase energy expenditure at first, the learning effect should reduce the necessity of subsidies in time [7]. Conversely, fossil fuel subsidizations still continue globally [7]. Another policy is putting a price on carbon externalities[7]. Carbon-prices would affect the coal industry substantially due to its high emission-coefficient and motivate investors to switch to gas [6,64]. At the same time, carbon-prices would make natural gas less attractive compared to renewables. Moreover, acquired funds from subsidies and carbon-prices can be redirected to enhance learning in zero-carbon technologies [7]. As a result, the carbon-pricing policies are expected to create an incentive towards reducing emissions and switching to zero-carbon technologies [7]. The SFD in **Figure 10** shows how policy efforts can help the transition into renewables.

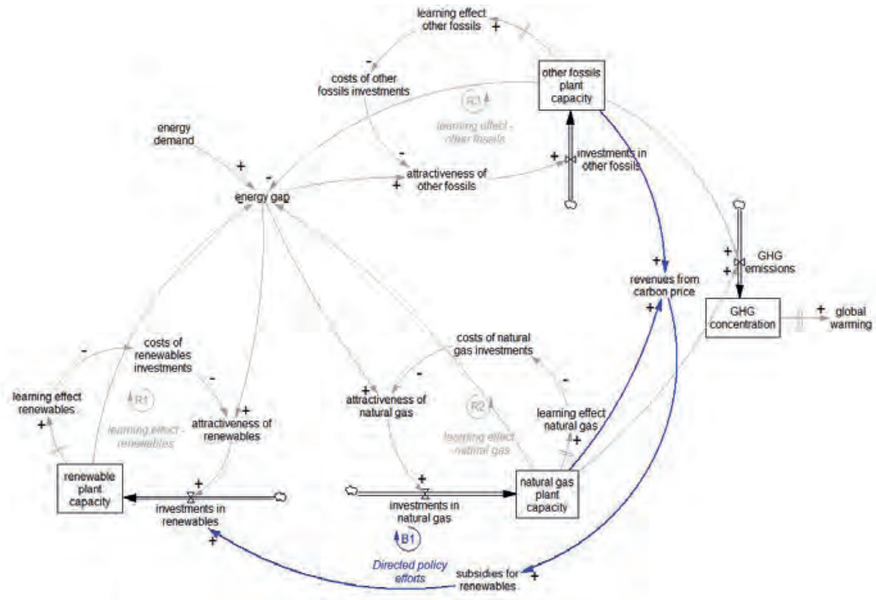


Figure 10 - SFD representation of how directed policy efforts can enable renewables.

While carbon policy mechanisms are debated globally, natural gas has been becoming more attractive. Gas prices have been getting competitive compared to other fuels due to the recent emergence of hydraulic fracturing technologies and shale gas. Competitive gas prices have been decreasing the relative attractiveness of investing in renewable technologies and persuading more investors to divert their focus from renewables (see studies [7,12,13] discussing the gas price and crowd-out mechanism). For example, wind energy technology producers have been reporting substantial losses due to the competitive natural gas prices caused by hydraulic fracturing production rates in the USA [12,73]. The investment competition is not only between natural gas and other fossil fuels. Rather it is between natural gas and all energy sources, not only renewables but also fossil fuels and nuclear [12,33]. The urgent demand for energy supply reduces our sensitivity to the fuel choice despite the environmental externalities (see studies [7,11–13] mentioning the insensitivity for fuel choice). Hence, growing energy demand does not discriminate fuels for the sake of continued economic growth [12]. Therefore, some authors [7,12,13] question which technologies natural gas investments replace in reality. Natural gas' direct positive effects and speed of development might lead to a default position of relying mainly on fossil fuels [12]. In parallel, the share of renewables has remained unchanged since the 1990s because additional fossil fuel capacities have also been added to the energy mix [7]. Hence, without policies that enable renewables, it is hard to assume that every gas investment is done "at the expense of other fossil fuels" [13].

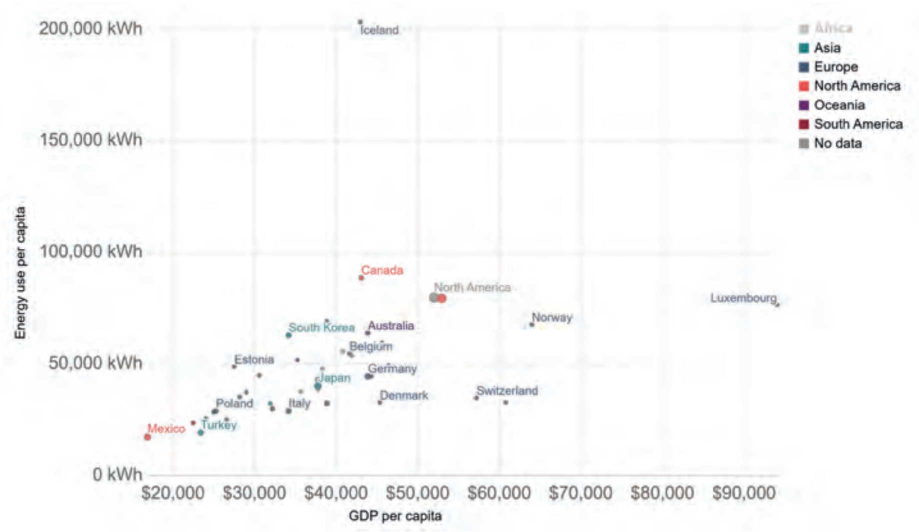


Figure 11 - The graph portrays the strong trend between energy use and GDP per capita[80].

Energy Rebound refers to the interlinkage between energy costs, global production, and global energy demand [13]. When energy costs increase, higher energy spending is expected throughout the world [13]. Contrarily, a decrease in energy costs does not necessarily reduce energy spending linearly. When the energy costs drop (i.e. affordable natural gas), this motivates an increase in global production [13]. Global gross domestic product (GDP) increases when more is produced with the same costs. An increase in global GDP would result in additional funds which would lead to an increase in production facilities. Therefore, an increase in global GDP will ultimately have an increasing effect on the global energy demand. As a result, even if the energy costs decrease significantly, only a percentage of that decrease returns back as an economic or resource saving. The complementary percentage is exerted as a means to increase global production and consumption. This effect is called energy rebound [76,77] and it can emerge by any affordable energy technology including natural gas.

Scientists tends to differ in their views about energy rebound. According to different authors, rebound can backfire by leading into more resource use [77] or offset the expected reductions in energy costs and fuel consumption [76]. Overall, energy rebound is hard to calculate due to high uncertainties, especially regarding macro-economic rebound (which is the effect of global natural gas prices) [78,79].

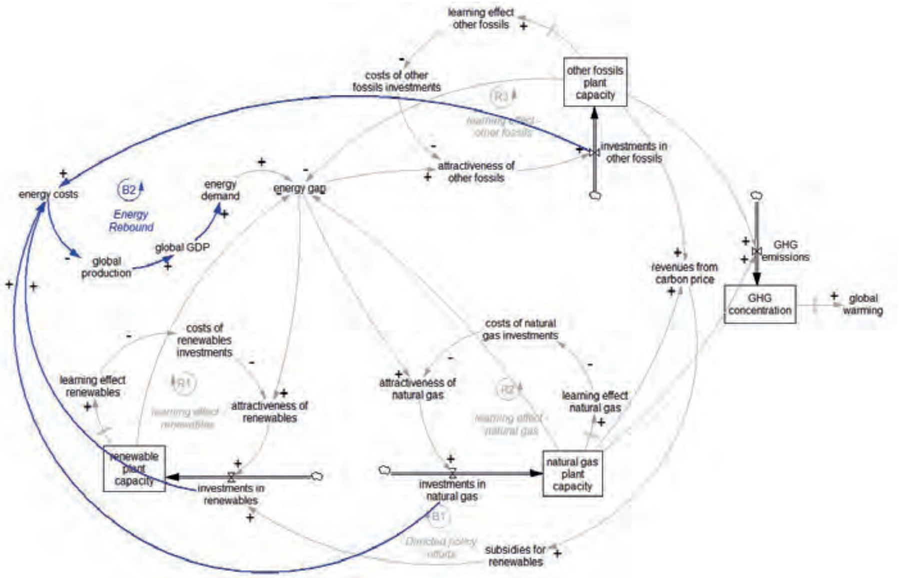


Figure 12 - SFD representation of how affordable natural gas can decrease the sensitivity to fuel choice due to increasing energy demand.

Even though it is hard to be sure about the magnitude of this dynamic relationship between energy prices, global GDP, and energy demand, there is a strong trend between energy use and a nation's wealth and growth as shown in **Figure 11** [80]. Furthermore, the causality between energy prices, global GDP, and energy demand still persists. After reviewing 100 different studies, Chontanawat et al. [81] discuss that the causality between energy to GDP is found to be more prevalent in developed OECD countries which are the countries responsible of a major share of the global emissions. In 2017, the average CO_2 emissions per capita in OECD countries were 9.02 tonnes while the average for the world is 4.35 tonnes [82].

Due to the challenges of calculating the exact rebound percentage [78,79], there may be two different outcomes of energy rebound. If energy rebound leads to a backfire, then using affordable gas might lead into increased resource use including fossil fuels [77]. If energy rebound offsets the saving percentage [76,79], then using affordable gas or cheap fuels cannot be a silver-bullet strategy to reduce the global energy costs. Even if we are uncertain about the magnitude of rebound, when we add the increasing trend of the global energy demand to the offsetting effect of energy rebound, it is safe to argue that increases in energy demand would reduce our sensitivity to the fuel choice and result in a crowd-out effect by pitting natural gas against all other types of energy sources. In his work, Baron [7] confirms this mechanism in action. Although the renewable energy capacities have been increasing spectacularly, their share in the electricity supply has remained unchanged since 1990 because a large amount of fossil fuels have also been added to the mix [7]. **Figure 12** depicts the energy rebound feedback.

Energy costs

This theme investigates various costs in the energy transition. Two sub-categories are used for this theme: electricity generation costs, and transition costs. *Electricity generation costs* refers to the financial viability of natural gas when generating electricity, including the cost of investments, maintenance, operation, and fuel prices. Several authors [1,10,33] argue that natural gas technologies are economically more viable than current renewable technologies. Natural gas' levelized cost of electricity (LCOE) is better than those of renewable technologies [83,84]. LCOE uses a life-time approach by dividing the average total cost to build and operate a power plant by the average total energy output [83,84]. Natural gas' overnight costs also perform better [83,84]. The overnight cost is an economic comparison method for investments that focus on the average total cost of building a power plant [83,84]. Therefore, natural gas often presents a better opportunity for investors. Due to renewables' high costs, investing in them would also increase the electricity price on the demand side (see studies [1,5,6,10,13,33] mentioning renewables' high costs). Hence, natural gas can also provide affordable energy to consumers. In 2017, 13.2% of the world population still did not have access to electricity [85]. Most developing countries have been increasing the ratio of electricity accessibility rapidly [85]. Expanding the electricity grid to new areas needs vast investments, especially to rural areas [85]. On one hand, natural gas can provide affordable electricity to certain rural regions because of low fuel prices and initial investment costs [14,62]. On the other hand, investing and expanding natural gas infrastructure creates a barrier against future investments in renewable technologies by increasing their relative costs [9]. Ahmed, & Cameron [12] argue that if natural gas is used to compensate intermittency, relative costs of renewable technologies would also increase. To illustrate, a 0.88% increase in renewable capacities were associated with a 1% increase in the share of fast-reacting fossil fuel technologies in the OECD countries [55]. Any cost increase on the generation side would also affect consumer prices (see studies [1,5,6,10,13,33] mentioning dynamics for consumer prices). In addition, complementing natural gas plants would not only be used for helping out renewables. If there exists a power plant and an energy need, these natural gas capacities will be utilized even though they would result in GHG emissions [12,13]. Overall, natural gas presents an opportunity to provide affordable energy for consumers and profitability for investors but only do so at the expense of increasing the relative costs of investing in renewables.

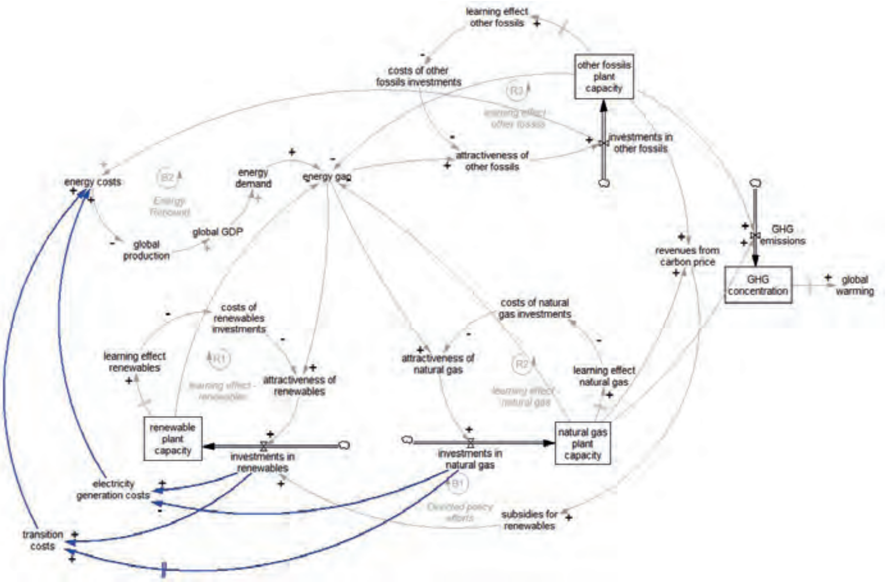


Figure 13 - SFD representation of how energy costs are affecting the energy rebound loop.

Transition Costs refer to the total costs which are associated with the transition into more sustainable energy systems. Natural gas is considered as a transition fuel to bridge polluting fuels to zero-carbon technologies. Natural gas plants would only be utilized until zero-carbon technologies emerge since gas still results in GHG emissions. Hence, natural gas investments present a short-term to medium-term solution for the energy transition as argued by several authors [6,12,33,40,63]. When emission pressures increase, investments have to be reallocated once more. Some authors [6,7,11,12,33] mention that these reallocations might make the whole energy transition more expensive depending on the timing of the transition out of gas. Furthermore, investing in soon-to-be-dropped technologies may delay the transition into zero-carbon technologies which would also lead to environmental repercussions [9,38]. Baron [7] argues that carbon-prices are not at the levels that they should be and they are still not fully directed at renewable technologies [7]. Even if they were directed at renewables, this would negatively affect the fossil fuel industry's electricity generation costs and thus consumer prices. Overall, natural gas presents an affordable transition solution in the short term while increasing transition costs into zero-carbon technologies in the medium-long term depending on the timing of the transition. In contrast, an immediate transition into renewables increases the electricity generation costs in the short term.

Energy costs are added to the model. **Figure 13** shows how affordable electricity generation costs of natural gas increases the energy demand through the energy rebound feedback. Additionally, investing in natural gas can increase the transition costs in the long-term, although natural gas' immediate electricity generation costs are lower than those of renewables.

Environmental impact

Environmental impact investigates the environmental effects of using natural gas as a transition fuel. According to the IEA [21], the electricity and heat generation sector is responsible for approximately 40% of global CO_2 emissions. Increasing emissions and the urgency of climate change is gradually affecting the perceptions of different technologies. **Figure 14** shows how GHG emissions can pressure the fossil fuel industry. Global warming increases the attractiveness of natural gas compared to coal, and attractiveness of renewables compared to all fossil fuels.

In this theme, we identified three sub-categories: replacing coal, GHG emissions, and other environmental effects. *Replacing coal* refers to the transition out of carbon-intensive coal power plants. Burning gas emits less GHG emissions compared to other carbon-intensive fuels as pointed out by several authors [1,2,5–7,10,33,64]. Hence, replacing coal, the most carbon-intensive fuel, with gas would reduce emissions. Thus, a shift from highly-polluting coal to less-polluting natural gas has been considered an environmental-friendly step in the energy transition (see studies [1,2,6,13,14,33,40,62,64] arguing how natural gas can replace coal and reduce emissions). Concurrently, Colombo et al. [6] mention that affordable gas prices and ample supplies would be an incentive to replace coal and enable other zero-carbon technologies further down the road if complemented with policy measures. Aguilera and Aguilera [64] mention that a carbon-tax would enable natural gas investments by deteriorating coal's relative position. Both authors [6,64] argue that competitive natural gas prices would support a switch out of fossil fuels and reduce emissions further down the road. In parallel, using gas has led to a local emission reduction in the USA [2,13,33] and the Netherlands [1]. Furthermore, some authors [2,33] argue that an emission-reduction might be expected if natural gas should ever become dominant in Asia. Natural gas' emission-reduction potential is shown in **Figure 15**. Attractive natural gas is forcing investors to transition out of more expensive and polluting fossil fuels. As a result, a switch to natural gas should reduce emissions caused by burning coal.

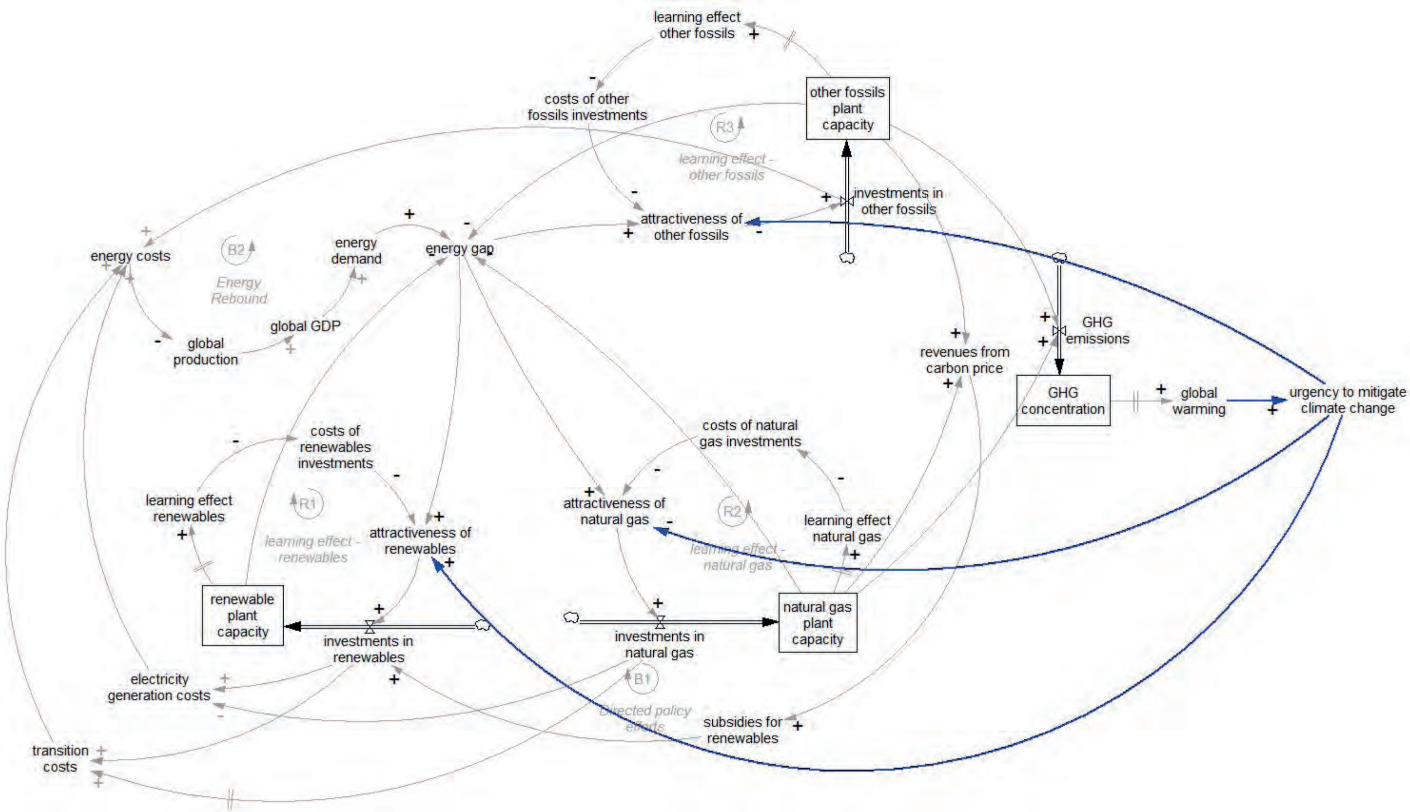


Figure 14 - SFD representation of how increasing emissions are resulting in an urgency to mitigate climate change.

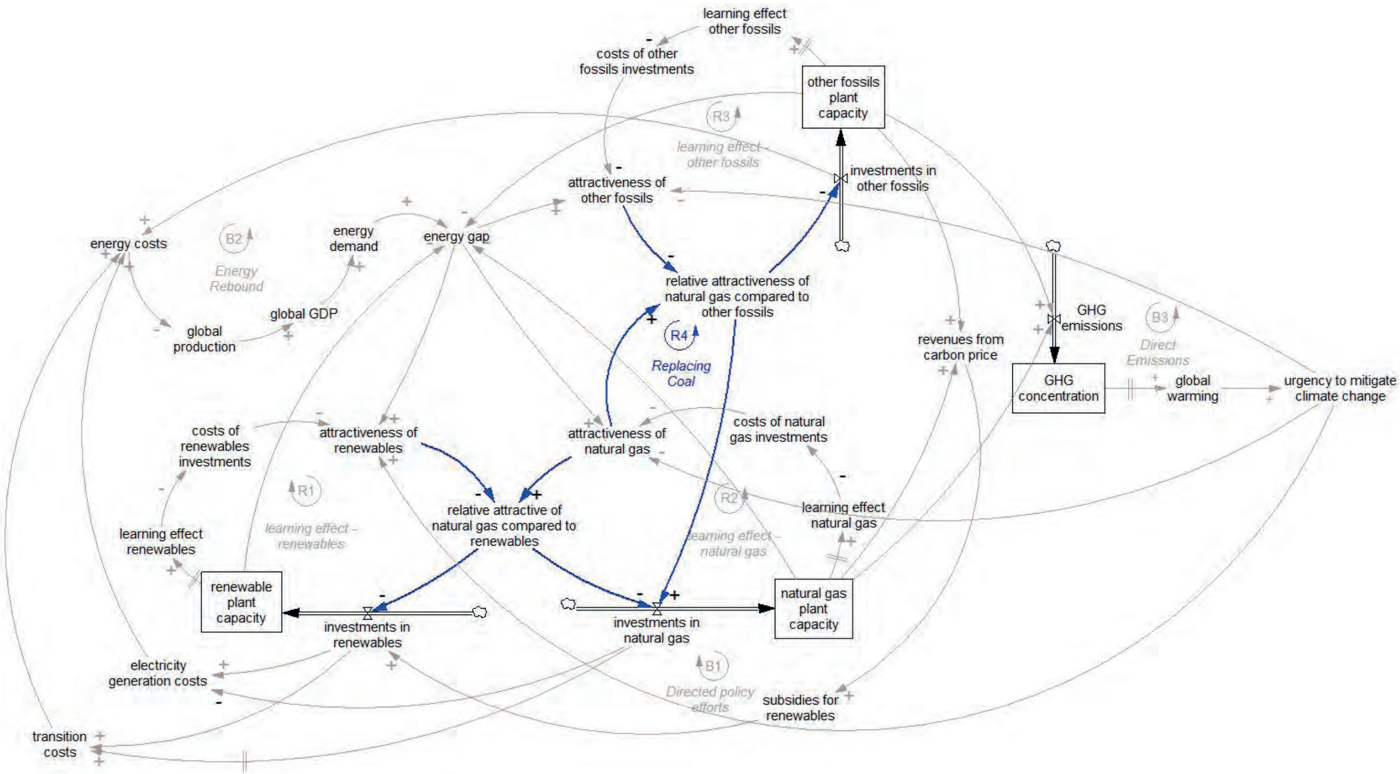


Figure 15 - SFD representation of natural gas replacing coal and reducing direct emissions.

On the other hand, there are counter-arguments where affordable gas prices did not result in an emission-reduction. Ahmed and Cameron [12] refer to Tracking Clean Energy Progress report [86] which reveals that the US shale gas advances had the opposite effect on Europe. Although the USA reduced its emissions with ample supply of shale gas, the competition in the fossil fuel market also incentivized US coal export prices to drop significantly. The affordable coal has been exported to Europe [7,37] and made it possible to keep the European coal plants running. **Figure 16** shows this behavior called carbon leakage [54]**.** Carbon leakage is a type of fossil spillover which stems from the *reallocation of industry* [87]. IPCC identifies fossil spillover as a broad concept that is used to discuss how emission-reduction policies are interrelated with changes in the industry infrastructure and implementations of technology [87]. To illustrate, *already extracted coal* will be used in someplace else in the world, if not used in the location where it was extracted. Arent et al. [13] emphasize the global scale of the problem and discusses that local abundant gas can have contrasting consequences for emissions in different regions. Meaning, coal spills over to other continents if it cannot compete with affordable gas in the local market.

The *GHG emissions* theme refers to the environmental viability of natural gas in terms of its emissions. Natural gas results in GHG emissions during various processes in its life-cycle: extracting, producing, transporting, and burning. Natural gas consists primarily of methane (CH_4) including a small percentage of other gases which also cause global warming including CO_2, NO_x, and SO_x. There were only two quotations on NO_x and SO_x emissions in the selected literature [6,33]. Both mentioned that natural gas emits less NO_x and SO_x emissions compared to other fossil fuels when burned. CO_2 and methane were the primary focus in the reviewed literature.

CO_2 dissolves much slower than it accumulates in the current energy configuration. If CO_2 passes the 450 ppm, this would reduce the world's chances of staying under global warming by 2 °C scenario significantly [23]. CO_2 emissions from natural gas are mostly caused by burning gas[8]. But, they also occur during *other* processes such as extraction, production, and transportation. Although recognized as inconsiderable compared to burning fossil fuels [39], these *other* CO_2 emissions are harder to measure because the range of emissions varies for different processing facilities and transportation methods [88]. Overall, CO_2 emissions are one of the riskiest GHGs because CO_2 has a significantly long atmospheric life-cycle [23]. After 100 years, only 60% of CO_2 emissions can be dissolved from the atmosphere. After 1,000 years, 80% of CO_2 emissions can be dissolved from the atmosphere. 10% of CO_2 emissions remain in the atmosphere even after 10,000 years [23].

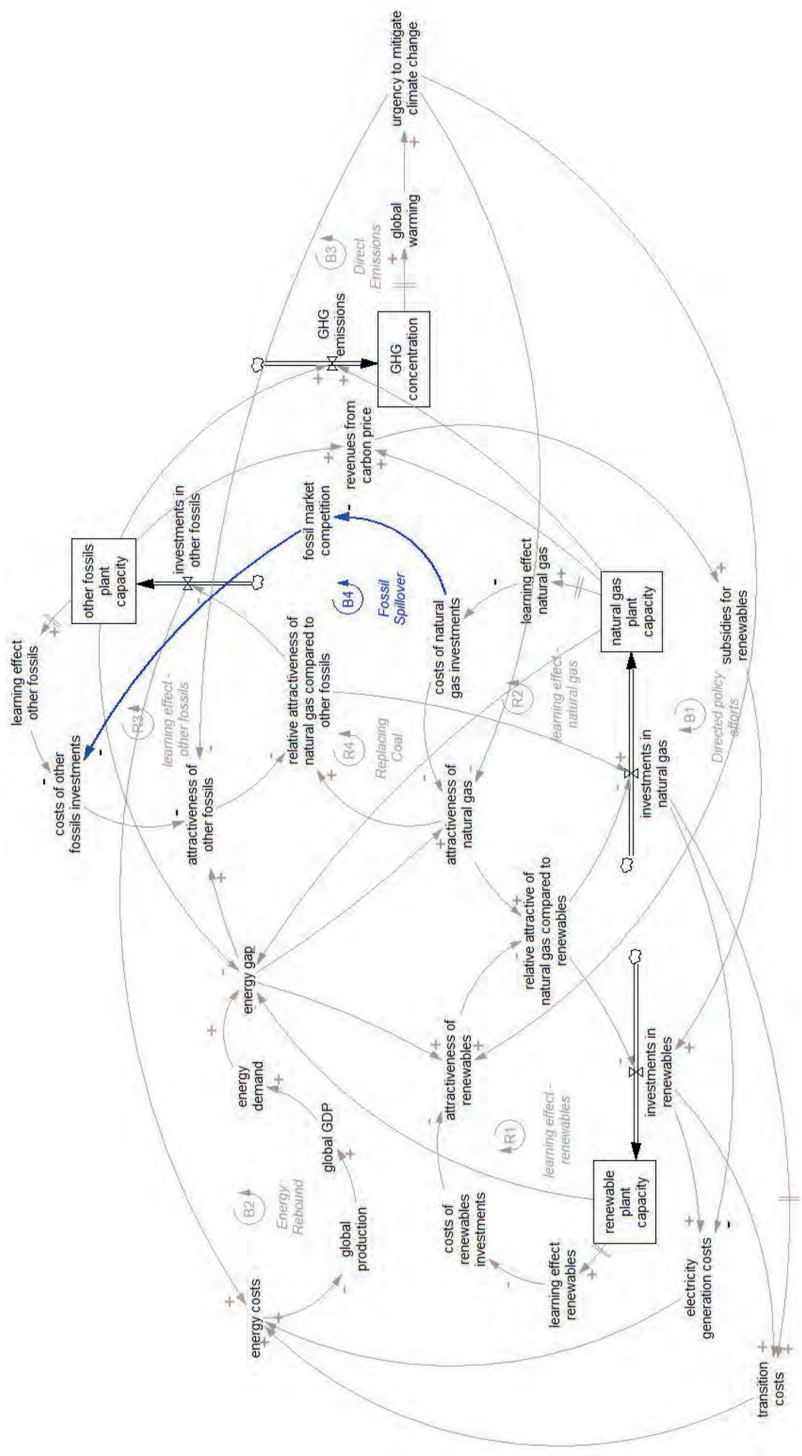


Figure 16 - SFD representation of how economic spillover of natural gas can result in carbon leakage.

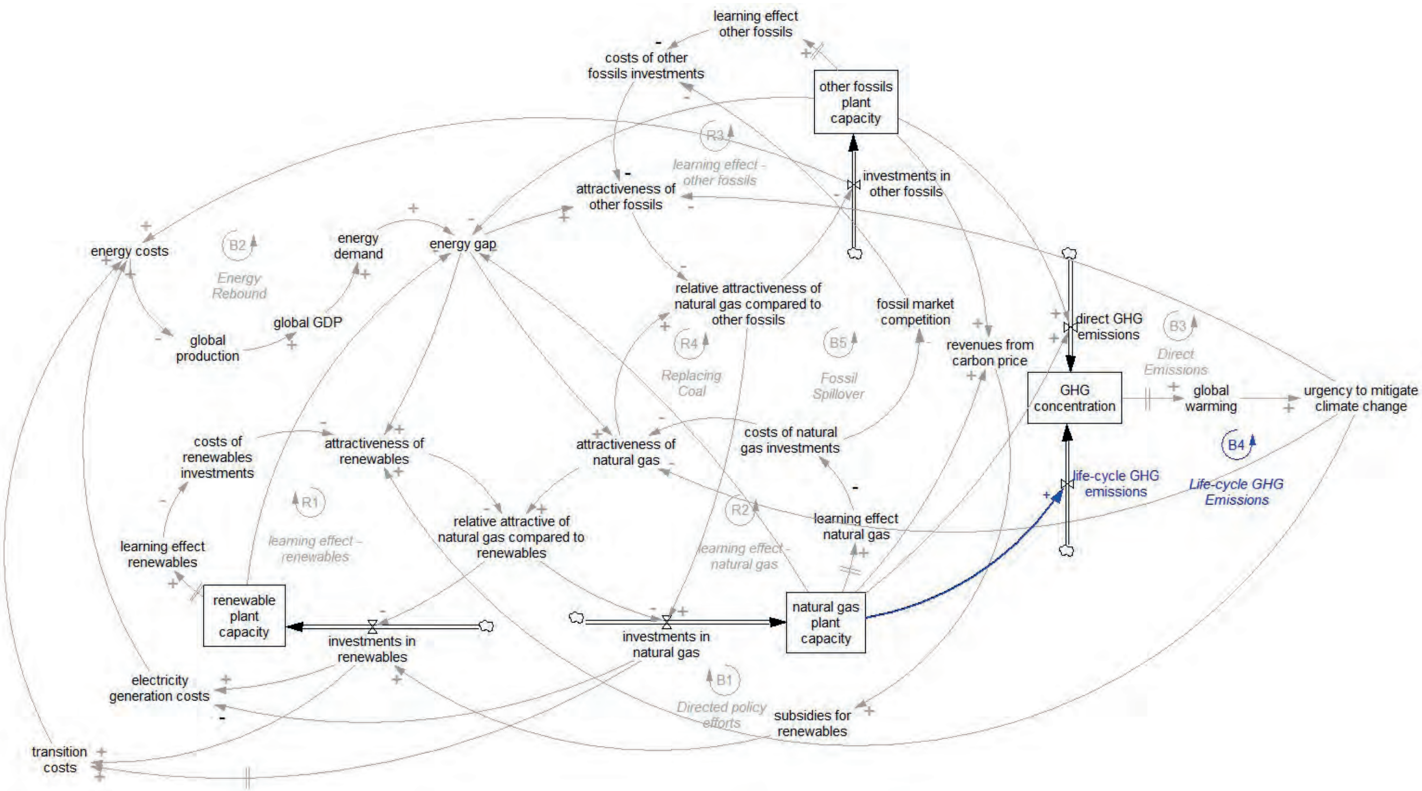


Figure 17 - SFD representation of how life-cycle emissions of natural gas can negate its emission-reduction benefits.

However, methane emissions contribute to the global warming potential significantly more than CO_2 [71]. Methane emissions stay in the atmosphere for about a decade before converting into CO_2 [23]. Because of this conversion, methane emissions compound the challenge of CO_2 mitigation. According to the IPCC's fourth assessment report [4], the 20-year global warming potential of methane is 72 times larger than CO_2's. Recent innovations in extracting shale gas provide the possibility for the world to keep extracting and using natural gas. However, because of methane emissions, shale gas could perform 20% worse than coal over a 20-year time-frame and 100% worse over a 100-year time-frame [71]. One source of methane emissions is flaring. Natural gases that are uneconomical to collect are flared. Flaring also converts certain unsafe gases into safer compounds [1]. Flaring takes place in refineries, gas plants, and during well-tests [1]. Natural gas still is a cleaner fuel compared to oil and bitumen in terms of methane flaring emissions *if* necessary precautions are taken [1]. Another source of methane emissions are accidental methane leaks and routine venting [1]. These are also called fugitive methane [40]. There are uncertain numbers and reports for the expected level of methane emissions in the gas life-cycle (see studies [2,33,89] mentioning uncertainties about methane emissions). To understand natural gas' actual effect on the global warming potential, comparative studies have to be done on life-cycle methane emissions of gas and total anthropogenic emissions [1]. **Figure 17** shows how overlooked life-cycle emissions of natural gas, both carbon and methane, can undo the direct emission-reduction benefits of burning natural gas.

Other Environmental Effects investigates other negative environmental effects of gas besides emissions. Some of these negative effects can be traced back to the hydraulic fracturing process. Extracting shale gas needs an excessive use of water as well as chemicals [1,2,59]. Water contaminations in Ohio, Arkansas, Texas, and Oklahoma were associated with hydraulic fracturing applications [1]. In addition, extracting gas leaves the ground susceptible to tremors and earthquakes [1,33]. In Oklahoma, the public associated earthquakes to hydraulic fracturing [1]. Similarly, in the Netherlands, the public has pulled back its support from natural gas extraction after tremors [33].

Discussion

Natural gas is currently being considered as a *transition fuel*: a temporary solution to mitigate greenhouse gas emissions while more sustainable technologies mature.

Without leveraging a transition fuel or supporting technology, the transition into zero-carbon emission may not materialize. However, increasing investments in natural gas will also initiate mechanisms that will delay the sustainability transition rather than help it. In this paper we advance the debate by reviewing the various mechanisms that will determine the impact of natural gas as a transition fuel, and by showing how these mechanisms interrelate. Our findings have implications for two streams of literature: technological innovation and transition management.

Technological innovation

Transitions into emerging and sustainable energy technologies originate from dynamic interlinkages between technical systems. A transition begins at the level of technological innovation at niches [90–93]. Mature technologies cannot prevent emerging technologies forever (see studies [9,38,90,91] on transition into emerging technologies) and emerging technologies often replace mature technologies by developing new processes and techniques [94]. Until recently, the *competition* approach has been used in the conventional setting of technology strategy which focuses on the *attack* and *defense* relationship between incumbent and emerging technologies [94]. With the increasing complexity of large technical systems [95], the multi-mode framework has provided a richer setting for discussing interactions amongst technologies (see *symbiosis, neutralism, parasitism, commensalism,* and *amensalism* in [94,96]).

Interdependencies between technologies are in a dynamic flux. *A bridging technology* (transition fuel) or *lock-in* can only make sense when dynamic relationships amongst technologies are considered. To elaborate, a bridging technology parasitizes on the existing technology and the emerging technology parasitizes on the bridging technology [96]. In theory, natural gas should parasitize on fossil fuels and help renewables while renewables parasitize on natural gas. As a result, renewable technologies need to gradually transform the existing system and be an indispensable element of the energy market. However, the very idea of *bridging* or *transition* means that spillovers are also involved in this process [96]. Thus, some authors argue that initial investments to a potential transition fuel could lock-out emerging technologies for extended periods (see studies [9,96–98] mentioning this dynamic). Treating technologies in isolation and focusing solely on competition cannot address this dilemma [94,96]. **Figure 18** shows two opposing functions that emerge out of multi-modal interactions between natural gas and other technologies [94,96]. Natural gas might help or hinder the energy transition depending on which function is dominant. Hence, to investigate whether one technology is *bridging* or a *lock-in*, the framework of choice should encapsulate a richer variety of interactions amongst different technologies [96]. Complexity arises from the interactions between technologies changing over time, due to changes in products, processes, structure of the industry, and companies in the industry [94]. Therefore, different technologies also evolve over time and thus change the interaction paradigm amongst technologies altogether.

To avoid lock-ins, it is crucial to understand the *trajectories* of each technology as well as the interdependencies amongst technologies. Technologies evolve through path-dependent processes due to the sociotechnical systems they reside in (see studies [97–100] on technological trajectories and evolutionary economics). Engineers define relevant problems for a technology depending on what users, markets, societies, or policies demand. Then, they define specific knowledge and a set of procedures related to the problems' solutions [98–100]. *Technical trajectory* is the direction towards which technological paradigm advances [100]. Carbon lock-in is a *rigid trajectory* which enables carbon-intensive technologies and locks-out other emerging technologies such as renewables [101]. A technological trajectory can become rigid when the incumbent technology has already taken advantage of *evolutionary improvements*, such as costs and performance characteristics [92,102]. Comparably, natural gas has benefitted from various evolutionary improvements [102]. On one hand, natural gas has many beneficial direct effects on renewables because of these evolutionary advantages (i.e. enabling an affordable energy transition, complementing renewables in energy reliability, etc.). On the other hand, natural gas can crowd-out renewables because of the same advantages [92,102]. In particular, one technological trajectory of natural gas has already transformed the energy transition paradigm. Hydraulic fracturing, which enables accessing natural gas in shale formations, has led to increased competition in the fossil fuel market, lower coal export prices, and carbon leakage. Ultimately, the technology trajectory affects which functions are dominant. Therefore, the technological trajectory and relative position of natural gas vis-à-vis renewables can both enable a higher share of renewables in the energy mix as well as becoming a dead-end in a carbon lock-in scenario.

Innovations in another technology niche can also challenge sociotechnical systems after sufficient knowledge has accumulated (see studies [90,91] on sociotechnical systems and niches). For example, while a trajectory towards creating feasible smart-grid applications would ultimately benefit renewables, a trajectory towards creating feasible carbon capture and storage (CCS) applications would synergize with fossil fuels. Therefore, managing transitions requires an understanding of the relations amongst various incumbent technologies and their innovation systems in relation to the various emerging technologies and their innovation systems [92,102]. Many scientists prioritize specific pieces of the transition puzzle according to their expertise [91] and unifying the accumulated knowledge can reveal novel insights for the energy transition. Therefore, synthesizing accumulated knowledge in different disciplinary approaches with multi-disciplinary frameworks [103] would further our efforts in investigating dynamic *interactions amongst technologies* and *trajectories of each technology,* and potentially reveal crucial elements to accelerate and smooth-out transitions [90].

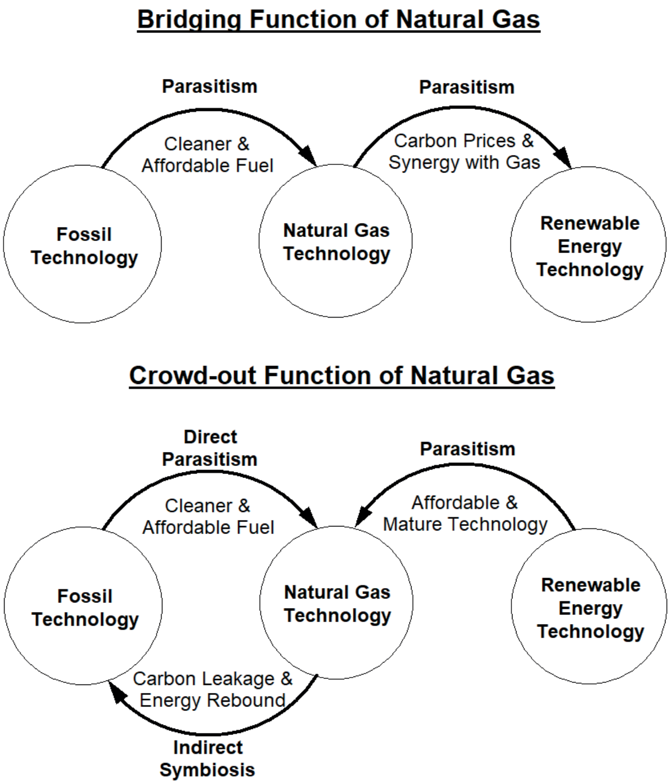


Figure 18 - Different functions of natural gas might help or hinder energy transition.

Transition management

Technological innovations are dependent on the context they aim to create a change in. Seeing this, different authors have come up with various frameworks to analyze how the context affects transitions, innovation, and policies. The energy transition, or transitions in general, are affected by the "socio-technical regime and landscape" [90,91], "techno-institutional complex" (TIC) [9,38], and "technology innovation systems" (TIS) [92,93]. Fundamentally, a technology or innovation cannot be separated from its social context [12]. Technology can be defined as a configuration that fulfills a societal function [90,104]. Technologies fulfill their societal functions by becoming part of our social patterns and routines [90]. A societal function is a set of activities that fulfills a certain societal need [105] and functions of technologies are born out of sociotechnical configurations [90,104]. Then, a transition is the switch from one sociotechnical configuration to another [90]. However, the alignments between existing sociotechnical systems can suppress the transition (see studies [90,106,107] discussing crowd-out and lock-in with different frameworks). Lock-in occurs as an unintended function of existing sociotechnical configurations as they are fulfilling other societal functions. If the *bridging* function is dominant, then natural gas is parasitizing on fossil fuels more than natural gas benefits fossil fuels, and renewables are parasitizing on natural gas more than natural gas parasitizes on renewables. Therefore, the *bridging* function of gas fulfills certain societal needs (e.g. fulfilling energy demand, polluting less than other fossil fuels, etc.). If the *crowd-out* function is dominant, then natural gas is in symbiosis with fossil fuels more than it parasitizes on fossil fuels. Also, natural gas is parasitizing on renewables more than renewables parasitize on natural gas. The *crowd-out* function of gas can be defined as a byproduct function (or unintended function) of fulfilling energy demand with the fossil-based sociotechnical configurations. Two functions of natural gas are in competition and the debate on gas exists because the levels and extent of the multi-modal relationships amongst technologies are uncertain. Therefore, successful transition policies depend on investigating which functions are supported at which level by the alignments between sociotechnical systems.

Understanding sociotechnical systems in detail can reveal possible obstacles for the energy transition. Notably, the *multi-level perspective* (supported by other frameworks such as TIS [92,93] and TIC [9,38]) puts forwards a broad analytical and heuristic framework which aims to understand why and how technological transitions succeed or fail. At the core of the framework, there are three levels of sociotechnical systems: technological niches, sociotechnical regimes, and sociotechnical landscapes [90]. A transition is an outcome of cumulative interactions between these different hierarchical levels of sociotechnical systems [90]. Innovations at niches challenge incumbent structures at the regime [90]. The landscape may pressure the regime due to slow and gradual changes in society, economy, or the environment, and thus create windows of opportunities [90]. And regimes can create policies to enable or hinder trajectories towards transition [90]. Finally, transitions occur when all these systems align together [90]. This transition management framework helps forming a better understanding of how to foster a sustainability transition [103]. Due to their roots, transition management studies mostly focused on case studies and applied qualitative empirical analysis so far [103]. However, transforming complex systems in written and mental databases [108] into qualitative and quantitative models can further our efforts in transition management studies.

Systems approaches and modeling practices can capture interactions between sociotechnical structures, interactions between technologies, and evolutionary stages of sociotechnical and innovation systems. These elements form the foundations of transition management and technological innovation frameworks [103]. Then, systems approaches can incorporate dynamic relations amongst sociotechnical systems while keeping innovation and transition systems as the focal point [109]. At the same time, long-standing transition management studies can also aid systems approaches and modeling practices. Transition management studies are a successor of two different lines of literature, evolutionary economics and sociology of technology, that have emerged in the 1980s [103]. In particular, sustainability transition management studies have received increasing attention over the last two decades. These studies can provide systemic content and written data to model innovations and transitions. Whereas, systems approach and modeling practices can provide the necessary tools and methods to investigate and experiment with modeled social systems. In this research, we hoped to benefit from this synergy. We have used documents which investigated natural gas' effects on energy transition and built qualitative system dynamics models intending to reveal feedback structures between sociotechnical systems of the energy transition. We were able to discuss issues such as the lock-in, crowd-out, and concept of transition fuel by using qualitative models because models can act as a boundary object [32,110]. Boundary objects are used for communicating and conveying understanding across individuals with distinct backgrounds [32,111]. By offering a shared discussion artifact, models can help stakeholders to (i) develop and analyze a problem, (ii) gain insights about a problem by challenging and questioning structures of the system, (iii) and pursue collaboration, negotiation, and consensus for debates (see studies [32,103,110,112,113] discussing various benefits of using models as boundary objects). In this research, we have used models as boundary objects to conjoin opposing arguments on natural gas. This approach helped us emphasize the existing sociotechnical systems in the energy transition and uncertainties regarding which function of natural gas is dominant. To conclude our discussion, synergizing systems approaches and modeling practices with transition management studies can advance our understanding in social systems' complex dynamics, and thus open up a space for seeking shared understanding amongst various stakeholders of energy transition regarding contrasting perceptions of our problems and their possible solutions.

Policy suggestions

The transition into zero-carbon solutions can be categorized in two phases. **Phase 1** is the transition from other fossils to natural gas and **Phase 2** is the transition from all fossils to zero-carbon solutions. These two phases simultaneously occur rather than a linear process. For both phases, we summarize two policy suggestions that can smooth-out the energy transition: clear road-map for natural gas and immediate implementation of a supranational carbon-price.

Many countries have long-term visions for climate-change mitigation and natural gas. Concrete road-maps or exit-strategies, which specifically discuss (i) upper-limits of natural gas and coal plants, (ii) fossil fuel capacity which is needed to transition out in a clearly specified time-frame, (iii) and how to manage and fund this transition, can prevent pitfalls in the energy transition. Without clear upper-limits for fossil fuels in the energymix and a concrete allowable time-frame to invest in fossil fuels (including natural gas), investments in gas might lead to extended investments in allfossil fuels. Unless the total allowable capacities are negotiated transparently, extended investments can create an overshoot in the fossil fuel capacity and thus the global emissions might pass over the 450 ppm. Therefore, first suggested policy is to have clear national as well as global road-maps and exit-strategies.

Furthermore, most of the articles which argue that natural gas could enable renewables in the medium time-frame, ground their arguments in the implementation of carbon-price. Although there are some active carbon-price policies on national levels, there are still no legislations in place that work on a global scale other than the promises made in the Paris. Moreover, there are still many countries that do not apply any type of carbon control. For the first phase of the transition, carbon-price could decrease the attractiveness of other fossils without hurting the attractiveness of gas much if limited to a certain level. For the second phase of the transition, carbon-price could be increased once more to decrease the attractiveness of gas this time and increase relative attractiveness of renewables. Yet, national carbon-price policies can hardly be enough to smooth-out the transition because the lack of a supranational carbon-price could easily lead to carbon leakage by displacing the *dirty* electricity generation to other countries with less carbon restrictions. Therefore, our second policy suggestion is to clearly identify a carbon-price implementation method, preferably on a global scale, and clearly define how this fund could subsidize renewable technologies or other zero-carbon technologies' learning.

Limitations and future research implications

Quantitative models help us perform experiments on system trends and policies where *dynamics of systems* can be investigated thoroughly. Thus, our policy suggestions can benefit from the quantification of these models. Secondly, challenging and expanding the boundaries of system models, both mentally and formally, is one of the intrinsic goals of system dynamics. Expanding the renewable technologies and literature selection might reveal new system structures. We have performed a literature review because peer-reviews in academic journals check the quality and objectivity of the academic work by default. However, using expert interviews and other types of primary data might also reveal new in-depth information about the structure of the system.

Conclusion

We have investigated the direct and indirect effects of natural gas on the energy transition. We conclude that overlooked indirect effects of natural gas can negate its direct benefits. In this research, we have taken a *systems approach* to investigate these systemic forces. We have underpinned several indirect effects that are caused by interlinkages between different technologies, conflicts in global versus local goals, and delayed responses in the system. We have done a systematic literature review on the indirect effects of using natural gas as a transition fuel to discuss the conflicting forces in the energy transition with the help of qualitative stock and flow diagrams. All things considered, there is an opportunity to help renewable technologies by supporting them with natural gas as long as the right steps are taken. As a mature technology, natural gas has been through more evolutionary processes compared to renewables. For this reason, natural gas can directly support renewable technologies in many functions such as balancing intermittency, providing reliable energy, offering affordable investments and consumer prices. Without these leverages from a supporting technology or a transition fuel, the reconfiguration of the energy systems into renewable technologies might be infeasible, overpriced and more importantly significantly delayed. However, taking advantage of a transition fuel comes also with challenges. Initial investments to a potential transition fuel such as natural gas could lock-out emerging renewable technologies for extended periods. Technology lock-ins occur as distant and delayed responses from the system and amplify the complexity of transition management. Overall, using system dynamics models as boundary objects helped us reveal conflicting views in the natural gas debate and stress the significance of indirect effects in sociotechnical systems' transition.

Human beings' next possible frontier is in understanding our social systems [114]. As social systems get more complex, sharing accumulated knowledge in different disciplines gains relevance. Achieving that requires crossing the boundaries of disciplines and applying analysis frameworks that can embody various methods, tools, and approaches within. In particular, systems approaches can be synergized with transition management studies to work as a comprehensive multi-disciplinary framework to investigate the dynamics of sociotechnical systems over time. As a next step, quantitative modeling practices can help us test our hypotheses on energy transition policies and system trends in simulation experiments [114]. The increasing urgency of climate change does not leave much room for overlooking interdependencies amongst sociotechnical systems in future decisions because even a simple blunder in a well-intentioned policy might lock the world in on a path where the window of opportunity is missed to create a climate-neutral world.

Footnotes

1,2 – We have used short-term as up to 20 years, medium-term as up to 40 years, long-term starting from 40 year to the future. Short-term and medium-term were determined from the natural gas plants' average economic lifetime which is 30 years [52].

20 years can be considered a short-term for the energy transition since a transition from natural gas in 20 years would mean the whole life-span of a brand new gas plant was not utilized in full.

40 years can be considered as medium-term because there are still ongoing natural gas investments (and there will also be future natural gas investments in the next decade or even more), which will depreciate again in the next 30 years.

For the long-term, we have decided to use 40 year+ because it also gives a 10 year additional time for achieving Horizon- 2050 goals if the goals are not already met by then.

3 – **Appendix B** features the coding tree that was used to design **Table 1**. The coding tree uses the same themes mentioned in the **Results** Section. **Appendix C** mentions how the readers can obtain the data table consisting of the corresponding quotations, providing evidence for each of the themes, and allowing the reader to trace these themes back to the reviewed studies.

4 – This assumption is true for variable renewable energy sources such as solar and wind technologies. To illustrate, as long as there is wind availability, a wind power plant would generate electricity even though if there is no energy demand. As mentioned before, solar and wind have been selected for this research. The decision for choosing solar and wind technologies is explained in **Appendix A**. That being said, there are also other renewable technologies such as bioenergy or hydropower which cannot be considered as intermittent.

5 – *Energy reliability is* about optimizing the balance between electricity generation and consumption. There are two discussed emerging solutions to tackle reliability challenges. One discussed solution is to store energy via various energy carriers (i.e. electrical batteries, compressed air, dammed water or hydrogen, etc.). The second discussed solution is to innovate grid infrastructure so that energy surplus in one local region could be easily transferred to another region where there is energy

demand [115]. The conventional electricity grid works as a one-way road, from electricity generator to electricity consumer [115]. *Smart-grids* work as a two-way road where electricity can flow freely between various regions with surplus and demand by using information communication technologies and smart meters [115]. Although working on these solutions could pave the way towards a sustainable future, they still require technological, environmental, economic, or infrastructural break-throughs (see studies [35,115–118] that mention several of these solutions and their challenges).

6 – In our learning feedback diagram, learning effect represents the effect a combination of economies of scale (the more we produce a technology, the more affordable and attractive that technology becomes) and accumulation of innovation (the more we know about a technology, the more affordable and attractive that technology becomes). Different learning types can be investigated in this case study [119].

7 – There are two discussed approaches for a carbon-price [7]. The first approach is to tax emissions (carbon-tax). The other approach is to create a tradable market-based instrument for emissions (emission-shares) [7]. In the latter, total allowable emissions would be decided on a national or global scale. The market-based instruments would be sold to organizations emitting GHGs [7]. A cleaner organization can sell its allowed emission shares to more polluting organizations. These carbon-pricing policies are expected to create an incentive towards reducing emissions and switching to zero-carbon technologies [7].

8 – Chemical formula for burning gas: $CH_4 + 2O_2 \rightarrow \mathbf{CO_2} + 2H_2O$. CH_4 stands for Methane (natural gas). It is burned by using oxygen, O_2. The result is carbon dioxide (CO_2) and water (H_2O). Therefore, when natural gas burns, it emits CO_2 emissions.

Appendices

Appendix A - Filtering method

We used Google Scholar, Scopus, Web of Science, ScienceDirect databases to access the data. Searching "Natural gas", "clean energy" and "transition fuel" as keywords in returned 585 results in total: 435 results in Google Scholar, 2 in Scopus, 74 in ScienceDirect, 74 in Web of Science (results from 15.06.2020). We have used our filtering method explained below to choose relevant papers. 42 papers were selected in this study. In these papers, a total number of 440 quotations were selected. Out of these, 177 were quotations about natural gas' direct effects and 229 were quotations about natural gas' indirect effects. These quotations were categorized with the coding tree explained in the **Appendix B.** The filtering method is explained point by point below.

According to IPCC's report on Renewable Energy Sources and Climate Change Mitigation [121–126], solar and wind power are one of the most abundant resources globally compared to other renewable alternatives such as bioenergy, hydropower, geothermal, etc. [121–126]. This makes solar and wind energy as one of the most scalable options when global climate mitigation are considered [123,126]. Therefore, for our research boundary, solar and wind energy has been selected for the boundary of this research for renewable technologies. Solar and wind technologies provide variable energy outputs and thus could be helped by natural gas technologies. On the other hand, other renewable technologies such as bioenergy, hydropower, and geothermal can provide reliable and continuous energy compared to solar and wind technologies [122,124,125]. Therefore, these renewable technologies do not need the synergy with natural gas to become a feasible and reliable renewable option. That being said, other renewable technologies such as bioenergy, hydropower, and geothermal are heavily dependent on local circumstances such as agricultural land availability, water availability, or ground-water availability [122,124,125]. These restrictions challenge these technologies in becoming scalable global solutions. For example, even if US has converted all of their corn into ethanol (renewable gas from crops for transportation), they would only be covering 20% of their gasoline consumption let alone cover their electricity production [56]. As a result, they do not present the global scalability opportunity such as solar and wind technologies present. Although these other renewables can be good opportunities for local instances to provide reliable energy, they have less chance of becoming "the" global solution for mitigating climate change and reducing emissions. For the fossil fuel technologies, coal has been selected for the boundary of this research. Coal is one of the most pollutant type of fossil fuels and many of the literature focuses on natural gas' availability because natural gas can phase the coal out in the short-term. As a result, our research specifically focuses on solar and wind energy, natural gas, and coal.

There are many papers from diversified journals which focus on the different aspects of the natural gas debate. Foreign policy and law journals do not focus on natural gas' viability as a transition fuel. Chemistry journals focus rather on technical aspects of natural gas than its transitional qualities. Some documents on decision-analysis and policy-making journals use natural gas as a peripheral topic. Although these documents include natural gas in their bodies, they do not capture the necessities needed for this research, and thus were filtered out.

Secondly, we have made a decision of excluding papers that are focusing exclusively on shale gas and hydraulic fracturing (fracking) out of this research. Shale gas is a type of unconventional natural gas which resides in the formations of shale rocks. The fracking method enabled us to use highly pressurized water to cut through the shale rocks to reach the natural gas inside these rocks. The fracking method has many environmental and policy uncertainties behind it. Adding shale or other unconventional gases would add a new layer of complexity to this research. This might have worked against the simplicity and straightforwardness that we sought in our theoretical model. Thus, academic papers which were exclusively focusing on shale, fracking and unconventional gases were left out of this research's boundary. However, there are still 6 papers which focus on shale gas in our analysis. These papers do not solely speak on shale gas and have relevant discussions on the natural gas debate.

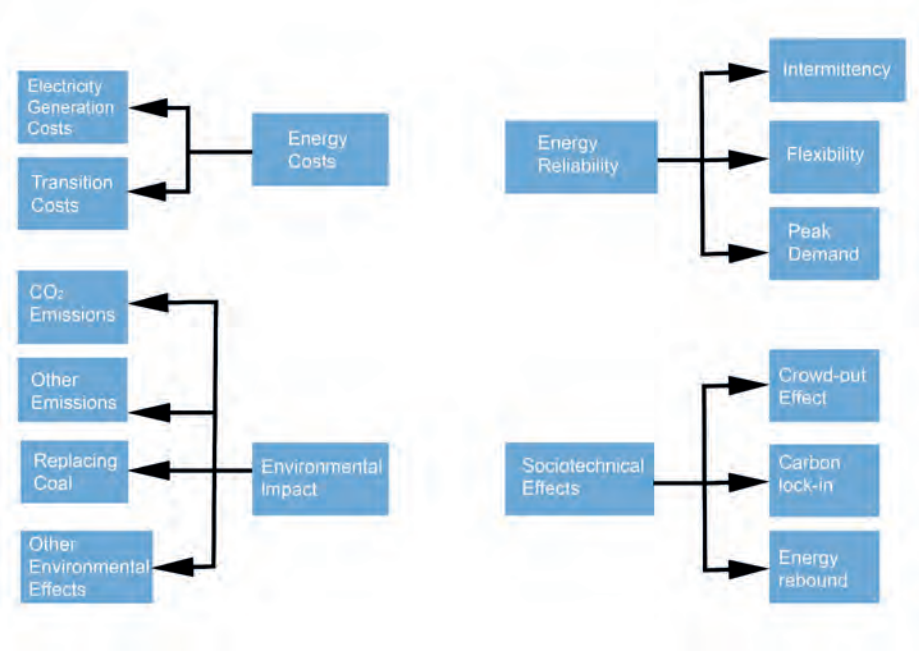
Thirdly, natural gas is not only used in electricity production but also as an energy carrier. Compressed natural gas (CNG), liquefied petroleum gas (LPG), and liquefied natural gas (LNG) are some examples of natural gas energy carriers. When we are able to transport gas in these processed states, it becomes possible to use these fuels for many purposes: heating residential areas, alternative fuel for cars, etc. These topics were also filtered out because electricity generation and energy carrier potential are only indirectly related to this research.

Hydrogen is another energy carrier which can store and transport energy. Hydrogen cannot produce energy as other fossil fuels or renewable energy sources can, rather it has the potential to store the produced energy and transport it. This topic was filtered out because storing and transporting energy in Hydrogen do not relate to natural gas debate directly.

Some papers were filtered out because they do not have all of the relevant keywords or topics. For example, some papers focuses on solely on natural gas, other types of fuels, energy in other sectors, etc. Although these papers include natural gas within their context, they do not present relevant content for our study and thus they were filtered out.

The resulting papers can be found in the **Table 1.**

Appendix B - Coding tree



Appendix C - Quotes of natural gas on energy transition

The authors of this paper have created a table consisting of all the quotations which were used to build **Table 1**. Due to copyright regulations of this journal, this data table cannot be shared in this publication. Interested readers can send an email to the corresponding author Cem Gürsan at c.gursan@fm.ru.nl. Upon request we can show the data table consisting of chosen quotations that was used in this study. In addition, we will share an example table of how these quotations were coded.The data table distinguishes direct & indirect effects of natural gas, positive, negative, and uncertain effects of natural gas. The data table also includes author names and quotations so that readers can trace why certain codes were selected.

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Chapter 4

District heating with complexity: Anticipating unintended consequences in the transition towards a climate-neutral city in the Netherlands

This research has been motivated by the academic works on co-creation for utilizing participative modeling approaches in a transition challenge. This study would not have been possible without the support and collaboration of Rotterdam municipality. Participative modeling workshops took place at the Rotterdam municipality with experts with different backgrounds during the first half of 2022. The article was later published at the Energy Research & Social Science journal in 2024 and was co-authored by Dr. Vincent de Gooyert, Dr. Mark de Bruijne, and Jonan Raaijmakers.

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Abstract

District heating systems are considered a feasible heating alternative to replace natural gas to mitigate emissions in cities. However, urban transitions are very complex because energy systems often operate in densely populated areas, which gives rise to all kinds of interdependencies in cities. These interdependencies can result in unintended consequences which can indirectly help or hinder urban energy transitions. Understanding these influences the transition to climate neutrality. This research investigates the lessons learned from a project conducted in Rotterdam: a high-density city in the Netherlands which is expanding its district heating systems. We use qualitative system dynamics models to explore the underlying complexity and to recognize indirect consequences of policies. Our results cover both technologically oriented and policy-oriented insights, contributing to the literature on transition governance in cities. On the one hand, the national and urban strategies in the Netherlands activate mechanisms that support cities with district heating systems such as Rotterdam. On the other hand, the same strategies could also lead to a potential rivalry between energy efficiency and energy security, which are both crucial goals in urban transition governance. Participative modelling provides policy-makers with an analytical tool to detect systemic dependencies which can be used to identify synergies and barriers among different energy policy objectives. This helps avoiding potential unintended consequences including the use of carbon-heavy systems and displacing investments from energy efficiency and renewable heating systems.

Keywords
district heating; energy transition; infrastructure interdependencies; socio-technical systems; system dynamics; feedback effects

Introduction

Decarbonizing cities is one of the most significant challenges of meeting the Paris agreement goals [1]. In 2016, the energy use in the built environment contributed to 17.5% of the global greenhouse gas emissions [2]. Natural gas accounted for 32.1% of the final energy consumption of the European built environment in 2019, of which 63.6% came from the heating sector [3]. Addressing urban decarbonization has resulted in numerous policies. However, a crucial component of decarbonization forms the replacing of natural gas by alternative heat sources. District heating systems are considered a feasible alternative for natural gas boilers because they are notably cost-effective in dense cities and cold climates compared to other alternatives and they can integrate renewable heat sources to mitigate urban emissions [4].

Energy systems are embedded in cities, especially in densely populated areas, which gives rise to all kinds of interdependencies. As an illustration, the Netherlands is increasing the tax on natural gas consumption to motivate the switch to alternative heating systems, including district heating systems [5]. On the other hand, such a price increase could also diminish the financial capacity of some households and thus inhibit replacing natural gas with alternatives. Therefore, energy systems are constantly shaped by their social and technical aspects [6], including but not limited to society, environment, urban culture, markets, policies, institutions, regulations, and technological innovations/disruptions [7]. In the absence of a thorough understanding, such socio-technical interdependencies can lead to unintended consequences in terms of ineffective policies that can work against carbon-neutrality efforts in cities, otherwise known as policy resistance [8]. Increasing our knowledge on socio-technical interdependencies can aid researchers and decision-makers in recognizing systemic patterns that can facilitate changes in urban energy systems by avoiding resistance to change, bottlenecks, and delays during urban energy transitions [9]. The objective of this study is to support the transition governance in cities through generating insights on how socio-technical interdependencies can impact urban energy transitions. To achieve that, we investigate the lessons learned from a project in the city of Rotterdam in the Netherlands, as this is a dense city with practical experience in switching from natural gas heating to district heating. We use qualitative models [10], accompanied with participative modeling techniques [11], to explore the consequences of interdependencies and indirect effects of policies during energy transitions in Rotterdam and beyond. Use of these models underlines that an open dialogue enables policy-makers and stakeholders to gain new insights for governing the complexity in urban energy transitions [12].

The research question is: what are the socio-technical interdependencies that can help or hinder carbon-neutral heating in Rotterdam? Our findings suggest that, on the one hand, the national and urban strategies in the Netherlands can activate mechanisms that can accelerate the transition away from natural gas in Rotterdam as well as other Dutch cities that already have a considerable district heating network [13]. On the other hand, interdependencies may also lead to a rivalry between different energy policies, namely policies directed towards energy efficiency and energy security, in the future, which are both crucial goals which are sought towards the realization of carbon-neutral cities. Unless decision-makers and stakeholders gain insight into socio-technical interdependencies, this rivalry may displace investments from energy efficiency and renewable heating systems towards high-temperature heating systems and carbon-capture systems.

Theoretical background

Energy systems as socio-technical systems

A system can be defined as interconnected set of elements that serves a specific purpose. Previous studies [14] have recognized energy systems as socio-technical systems because they cannot be separated from their social counterparts [6]. Overall, energy systems produce, process, and distribute specialized services [9], which facilitate the functioning of cities by satisfying societal needs [15]. Energy systems can be discussed as socio-technical systems in themselves, as well as being a significant component of the urban socio-technical system [16], depending on the scope of the analysis [12]. In this paper, we focus on the broader urban socio-technical system, in which energy systems are embedded in, to highlight the interactions between energy systems, policies, and cities.

From a transition governance perspective, energy transitions occur as a result of the dynamic interactions in the urban socio-technical system. Notably, the multi-level perspective framework [17] offers a heuristic approach for understanding the interactions in the socio-technical system that can influence transitions. At the core of the framework, there are three levels in socio-technical systems: regime, niche, and landscape. The regime level accounts for the societal orientation and coordination of activities that shape the stability and change of the urban energy systems. Regime actors (e.g. governments, municipalities, energy companies) create plans and policies for energy system maintenance, investments, and transitions. Innovations and disruptions at the niche level challenge the existing systems and regime, leading to optimizations and transitions in the energy system. Finally, the landscape level refers to deeper structural events in the external environment (e.g. climate change, wars, financial crises), which can exert pressure on the regime level and create a window of opportunity for a system reconfiguration. Transitions in energy systems occur when the interconnected elements align and thus allow for a change in the system at large [6]. Especially in compact urban areas, socio-technical interdependencies can easily transcend the system and sector boundaries and thus lead to feedback mechanisms with unintended consequences for policies and the city [18]. Therefore, the challenge of decarbonizing cities calls for an approach that takes the socio-technical interconnectivity into account [19].

Energy systems evolve path-dependently [20], which is another factor contributing to the complexity of urban transitions. Today's decisions will heavily impact which urban heating systems will be available and feasible in the future [21]. Selecting a specific energy system will have a positive impact on certain heating systems, while negatively affecting others [22]. This, in turn, affects the available pathways for future energy systems, otherwise known as the *technological trajectory* [23]. Thus, implications of energy decisions can materialize over a long time horizon, which calls for considering the perpetual changes within the built environment [6]. Such an interdependent nature and long-term consequences imply that urban energy transitions are non-linear, can easily transcend system and sector boundaries, and thus have unanticipated and sometimes counter-effective consequences. These characteristics make the urban energy transition a suitable topic to be investigated via a systems thinking approach [10].

Systems thinking for socio-technical interdependencies

Systems thinking [10] sheds light on the cause-effect relationships in complex problems such as urban transitions. These cause-effect relationships are seldom unidirectional but often work both ways, which results in feedback effects. Feedback effects occur when the interdependent elements in (socio-technical) systems affect each other and, through closed causal chains, themselves. This can lead to self-reinforcing or self-balancing mechanisms, which impact the system behavior in unexpected ways. These feedback mechanisms are a prominent source for policy resistance [6]. Systems thinking [10] investigates and explains such feedback mechanisms that can significantly help or hinder urban energy transitions [6,9].

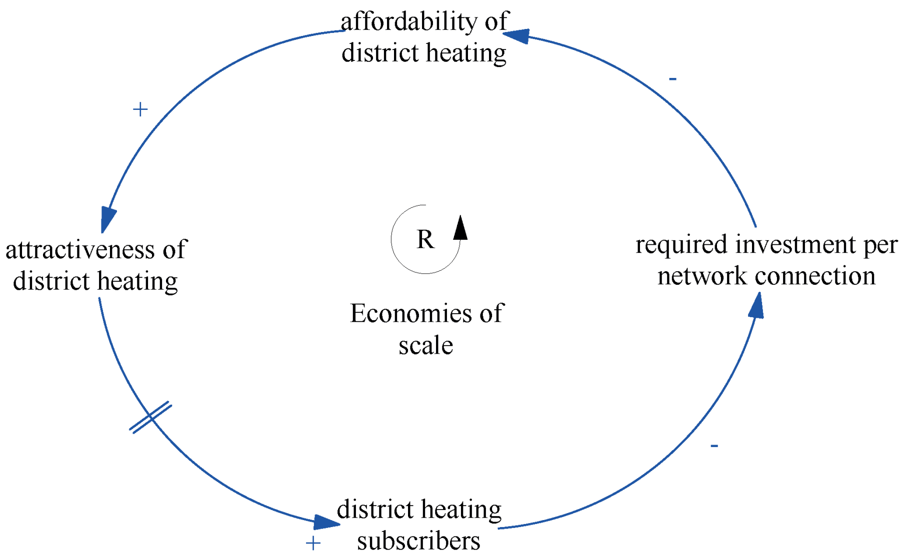

Figure 1 - Example of reinforcing feedback. Arrows indicate causal connections. An increase in one variable leads to an increase (+) or decrease (-) of the next variable, sometimes with a delay (||).

We illustrate two different types of feedback effects with two examples. **Figure 1** shows a reinforcing feedback that illustrates the economies of scale effect for district heating systems. The largest investment for heat networks concerns the installation of the main supply and return pipes, as connecting individual buildings to the main pipeline requires a smaller investment in comparison. As the scale and number of users of the heat network increases, the investment cost per network connection reduces significantly, leading to an economies of scale effect [24]. In turn, this will motivate more citizens to connect to the cost-effective heat network. The "|| "on the bottom left arrow in **Figure 1** indicates that the effect of an increase in *district heating attractiveness* on the number of *district heating subscribers* is not immediate but occurs with a delay. In this type of feedback, systems elements reinforce each other because an initial increase (decrease) in a variable lead to further increase (decrease) of the same variable through other system elements. Reinforcing loops amplify the initial change in the system.

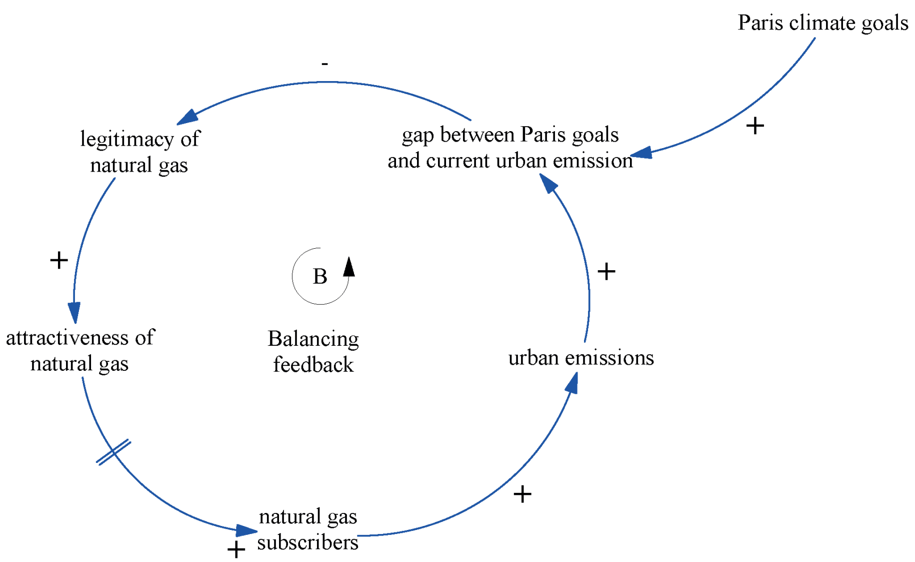

Figure 2 - Example of balancing (B) feedback. Arrows indicate causal connections. An increase in one variable leads to an increase (+) or decrease (-) of the next variable, sometimes with a delay (||).

Figure 2 presents a balancing feedback example. Households using natural gas produce urban emissions. When unchecked, these urban emissions will continue to increase and negatively affect reaching the Paris climate agreement milestones. As a result, more severe actions will be needed to replace natural gas with alternative heating systems until the built environment is natural gas-free. In this type of feedback, system elements change until the goal or limit is reached. Balancing feedbacks have a stabilizing or limiting effect on the system since they seek an equilibrium. Here, an increase (decrease) in one variable will eventually lead to the decrease (increase) of the same variable through other system elements. Balancing loops will therefore resist against and slow down a change in the system, hindering transition policies [8].

System dynamics (SD) approach, under the systems thinking umbrella, utilizes modeling techniques to generate insights on the feedback structures in complex systems [10]. Qualitative SD models, when accompanied by participative modeling techniques [25], can generate insights into interdependencies and their effects on urban energy transitions [26]. Although there has been a call for utilizing systems approaches to untangle the interdependent mechanisms in energy transitions [27], few articles apply systems thinking and analysis approaches to reveal the impact of socio-technical interdependencies on urban energy transitions[1]. Our research aims to fill this gap by generating insights into systemic mechanisms that can influence urban transitions by utilizing SD modelling techniques.

Methodology

We use qualitative models as a way to structure and generate insights on how socio-technical interdependencies impact urban energy transitions. Causal models are an intuitive way of describing the causalities and feedback processes underlying socio-technical systems [28]. Qualitative SD models, specifically causal loop diagrams, can be utilized to map feedback mechanisms for a richer understanding of their reinforcing or disrupting nature on the overall system behavior [10]. Participative modeling techniques, specifically group model building (GMB), allow researchers to collect interdisciplinary knowledge from experts and to scope and analyze a complex problem by highlighting influential interconnections and mechanisms [11,25].

A myriad of socio-technical elements affect urban energy systems and each effect can be interpreted divergently by different stakeholders [29]. Each stakeholder uses an abstract mental model of how the world operates built from real-life observations to intuitive assumptions [30]. Therefore, qualitative models can seldom encapsulate or verify every interpretation of assumed causalities in the system structure [31]. Rather, qualitative SD models, when combined with participative modeling techniques, can support researchers to openly explore and discuss how different stakeholders view, experience, and act on indirect effects [11] caused by socio-technical interdependencies [19] to support transition governance efforts [8]. For these reasons, we adopt an interpretive approach to make sense of the feedback structures within the stakeholders' mental models to identify issues to consider in future decisions [31]. We also highlight interconnected mechanisms to start an open dialogue between experts and policy-makers for supporting transition governance efforts [12]. Resulting models can be used as a discussion tool by stakeholders with different backgrounds to improve the communication and collaboration across sectors and departments [6]. Thus, they put forth a way to explore and highlight indirect consequences [19] that researchers and decision-makers should take into account during urban transitions.

To answer the research question, we utilized a single case study as the research design [32], as illustrated in **Figure 3**, on the transition from natural gas heating to district heating in Rotterdam. Our data collection consisted of an iterative data

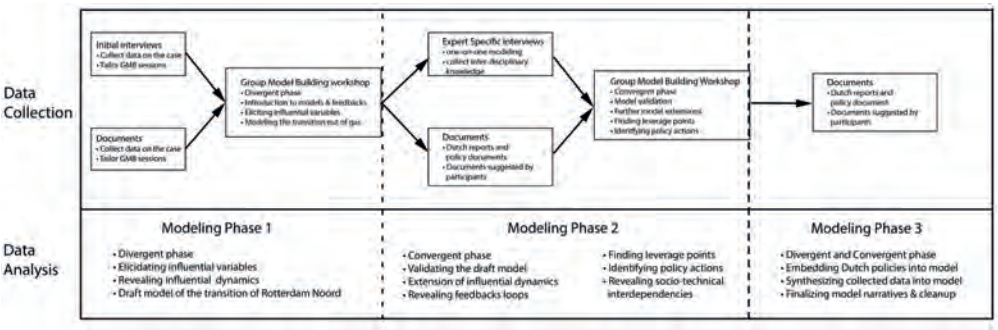

Figure 3 - Data collection and analysis methods used in the Rotterdam case, shown in a flow chart.

4

Table 1 - list of research participants

Responsibility	Type of organization	1. Semi-structured interviews	1. Workshop	2. Semi-structured interviews	2. Workshop
Advisor & Project expert	Municipality	x	x		x
Urban designer	Municipality		x	x	x
Climate adaptation	Municipality		x	x	x
Area manager	Municipality		x		
Urban development	Municipality		x		
Financial advisor	Municipality		x		
Neighborhood manager	Municipality		x		x
Neighborhood manager	Municipality		x		
Sustainability manager	Housing association	x	x		x
Sustainability manager	Housing association				x
Account manager	Grid operator		x	x	x
Project expert	Energy company		x	x	x
Technical expert	Energy company		x	x	x
Transition consultant	Consultant		x	x	x
Transition consultant	Consultant		x	x	x
		2	14	7	11

triangulation process [32] that included semi-structured interviews, document reviews [31], and participative modeling workshops [33] with influential actors as shown in **Table 1**. For the data analysis, we built qualitative SD models along with research participants in participative settings [11] to reveal, illustrate, and analyze the feedback mechanisms that can help or hinder the energy transition in Rotterdam.

To elaborate the data collection methods, we first reviewed policy documents [31] on the Dutch energy transition(s) and reports on prospective heating systems for Rotterdam and the Netherlands. Next, two interviews were held with project gatekeepers to find impacted stakeholders. These actors were invited to participate in two participative modeling workshops and interviews to collect cross-sectoral knowledge from impacted actors [34]. A second round of interviews allowed us to evaluate and advance the ongoing modeling efforts with research participants and [35] and provided them the option to share important sectoral knowledge which might have gone unnoticed during workshops [36]. The final stage of document revision allowed us to evaluate the identified causalities and dive deeper into the socio-technical interdependencies in Rotterdam [37]. This iterative process [38] allowed us to collect enough data to reveal influential causal links and study the mental models of stakeholders [11] which helped us explain how feedback effects and systemic mechanisms can impact urban transitions during the data analysis [8].

To elaborate on the data analysis methods, we utilized causal loop diagrams, a modeling approach under the SD methodology umbrella. Causal loop diagrams are modeled by connecting causal links, which are revealed during the data collection, into a systems model. These diagrams can be built by modeling experts in a non-participative setting and/or in a participative setting where influential stakeholders model the system together with an expert as a facilitator. In this research, we utilized a participative model building approach, called GMB, which is also under the SD umbrella. In collaboration with research participants, we built, evaluated, and advanced causal loop diagrams to bring about a more holistic view of the urban energy transition in Rotterdam [8], by identifying the feedback processes that can help or hinder the substitution of natural gas heating with district heating [20]. Resulting models embed the discussions and lessons learned from Rotterdam.

System dynamics

SD is an approach for analyzing and modeling the behavior of complex systems over time, facilitating an understanding on how different elements interact with each other and drive the behavior of system at large [10]. Hence, SD models can be used to analyze the causal interactions behind feedback mechanisms [28] that could influence urban transitions in unique ways in every city [39]. As **Figures 1 and 2** show, models are built by connecting variables with causal arrows. Different annotations on the causal arrows are used to explain the nature of the causal relation. A "+" sign on a causal arrow implies that causally connected variables change in the same direction: if one variable increases, then its causally connected variable moves in the same direction and thus also increases. A "-" sign means that the connected variables change in the opposite direction: if one variable increases, then its causally connected variable decreases (and vice versa). A "||" sign implies that the causal effect happens with a time delay. A variable can influence itself through other variables due to the feedback structures [6]. The reinforcing and balancing feedbacks are represented with the letters **R** and **B**, respectively. For this research, we used causal loop diagrams [10] because they allow an accessible representation of feedback mechanisms for those who may not have a background in modeling.

Group Model Building

GMB approach relies on participative workshops in which stakeholders formulate the structure behind a complex problem [40]. GMB is both a data collection and analysis method. The discussions during workshops enable researchers to collect data on influential causal links, which are then modeled analyzed by research participants under the supervision of process facilitators and expert modelers. GMB approach can be categorized as action research where modeling experts facilitate problem owners in participative workshops to understand and intervene with their own complex problems. The model-building process makes use of structured participative activities captured in scripts [41] through which participants are encouraged to co-create new knowledge on highly interconnected issues [42]. In the workshops, stakeholders can create "maps of feedback structures" [43] that explain system behavior and identify leverage points for future decisions. Models are built with research participants in a step-by-step manner to capture the interdisciplinary knowledge of interdependencies and to assess if participants agree with the incremental extensions on the model [8].

We conducted two workshops of 3 to 4 hours each. Each workshop was led by two facilitators, including one native Dutch speaker to overcome potential language barriers [31]. Preparations for the workshops started in December 2021 and workshops took place in April and May 2022. We aimed at involving a diverse set of participants to ensure the relevance and inclusivity of viewpoints. Fourteen participants attended the first workshop and eleven the second, which generated exchanges of arguments and drove the model-building process.

Case description

Home to approximately 652,000 citizens, Rotterdam is one of the biggest cities in the Randstad conurbation area in the Netherlands [44]. It is a heavily industrialized city with the largest seaport in Europe where many logistics, petro-chemical, and energy companies are located [45]. In 2021, one third of Rotterdam's CO_2 emissions (~2.3 million tons) were produced by the built environment [46]. Therefore, the urban heating transition is an essential part of Rotterdam's decarbonization goals. Although natural gas is still discussed as a feasible energy source and/or transition fuel in other countries [6], the Netherlands have decided to phase out natural gas [5] in the context of the Paris goals and gas production-related earthquakes in the Groningen region [47].

District heating systems are hot-water carrying grids connecting urban buildings with central heating systems. They are considered as a substitute for natural gas in Europe since they can be scaled up to accommodate the high heat demand in cities [48]. They can use different water temperature regimes depending on the city's needs: for cities with low heat demand and an energy-efficient built environment, lower-temperature water regimes can be used, whereas cities with poorly insulated buildings need to use a higher-temperature water regime. The choice between low- or high-temperature network affects the compatibility of central heating types, required piping diameters, required heating equipment in households, required energy efficiency levels in the system design as well as the energy consumption/costs of the city[3]. The heat for Rotterdam will come from a waste-to-energy plant that incinerates municipal waste [49]. For the future, the city of Rotterdam considers several heating solutions, including residual heat from industry, waste-to-energy plants, geothermal energy, and aquathermal energy. Notably there is an untapped residual heat potential in the port, which can be utilized until other low-carbon systems develop, such as geothermal and aquathermal energy [46]. Heat pumps could be a prominent individual heating solution competing with the district heating system. However, the initial investment costs for heat pumps and required refurbishments present a significant barrier for the adoption of these individual solutions [50][4].

The project location consists of dense neighborhoods in the city center, and most of the buildings are from the pre-war era with low thermal insulation. These buildings require a high-temperature heat network unless notable investments in energy efficiency are made. This also implies that many of the buildings cannot use heat pumps without significant refurbishments. On top of that, there is mixed ownership in the neighborhood: 60% lives in social housing and 40% is comprised of private owners and municipal buildings. There are many small owners' associations, which increases the complexity of decision making [51]. A significant number of residents face financial challenges and do not consider sustainability as a priority. The project neighborhoods were selected as promising locations for an initial expansion of the existing heat network. A total of ~10,500 households in the project location, are considered to connect to the heat network until 2025. Potential opportunities and challenges to connect these neighborhoods could inspire future transition projects elsewhere in the Netherlands and beyond.

More information on the methods, case, workshops, and research collaborators can be found in **Appendix A.**

Results

Our findings show that national and urban-level strategies can switch out of natural gas to district heating systems. However, socio-technical interdependencies may activate mechanisms that may decelerate or delay the transition towards carbon-neutral heating. Notably, our results reveal a potential rivalry between two crucial policy goals for carbon-neutral cities, namely energy efficiency and energy security, as a result of existing energy transition plans and policies. Bottlenecks during the transition towards carbon-neutral heating could delay investments in energy-efficiency of the built environment, prolong the use of carbon-heavy heating systems, and warrant future investments in carbon capture and storage (CCS) or carbon capture and utilization (CCU) systems [5].

National strategy to replace gas with district heating

Figure 4 shows a technology-adoption model that was adapted for the natural gas and district heating systems [6], comprising the national strategy to transition from natural gas to district heating. In general, existing heat networks are projected to replace natural gas at limited costs, significantly mitigating urban emissions [5]. Increased taxes on natural gas, incentives for heat networks, and aging gas equipment/infrastructure are factors that positively influence the relative attractiveness of district heating compared to natural gas, hence supporting the transition towards district heating systems.

The Netherlands has adopted several policies to replace gas in the built environment while ensuring urban mitigation and energy security, as shown in the reinforcing feedback loop **R1** in **Figure 4**. To mitigate urban emissions, new natural gas connections have been phased out since 2018 and the Netherlands aims to cease gas consumption in urban areas by 2050 [5]. The Netherlands has been gradually increasing taxes on natural gas consumption. However, to ensure energy security, citizens are allowed to use existing equipment until 2050. This measure is in place to allow enough time for households and alternative heating systems to replace natural gas but it also prolongs the use of natural gas for urban heating. Alternative heating systems, such as the district heating systems, are expected to develop sufficiently to replace natural gas before 2050 due to these national regulations [5].

For cities with existing heat networks, network expansion is one of the most affordable options to replace natural gas (see feedback loop **R2**) [5]. Nevertheless, each heat network expansion project requires a minimum number of connections and consumers to compensate for the investments to expand the heat network [52]. Large district heating networks offer better business cases and cash-flow profiles for network operators [53] — an economies of scale effect [24]. In an expanding heat network, infrastructure and input costs are shared by more users while the costs do not increase at the same rate as the number of new users. As a result, increasing the network's scale leads to cost reductions for deploying the heat network. This cost advantage can be passed on to clients in the form of lower energy bills [52], reinforcing the affordability of district heating systems. Therefore, more network subscribers render the district heating systems more appealing from a financial standpoint, thus accelerating the replacement of natural gas in the built environment.

A systemic trap while replacing gas: energy-poverty

Figure 5 shows a hindering mechanism for the substitution of natural gas, triggered by increasing natural gas prices. On the one hand, increasing prices makes alternative heating systems financially more attractive in the long run and thus is expected to accelerate the transition away from natural gas. On the other hand, increasing prices impact energy-poor households disproportionately, which would leave them with less financial capacity to invest in alternative heating systems [54]. Consequently, high energy prices could keep energy-poor households dependent on natural gas heating longer, creating a self-reinforcing effect on energy poverty and decelerating natural gas replacement.

The remaining gas customers may face higher energy bills as fixed costs of the natural gas infrastructure are borne by smaller numbers of households, as shown in feedback loop **R3** in **Figure 5**. Energy companies can distribute gas for their remaining customers until 2050 [55]. In the long run, energy companies will lose

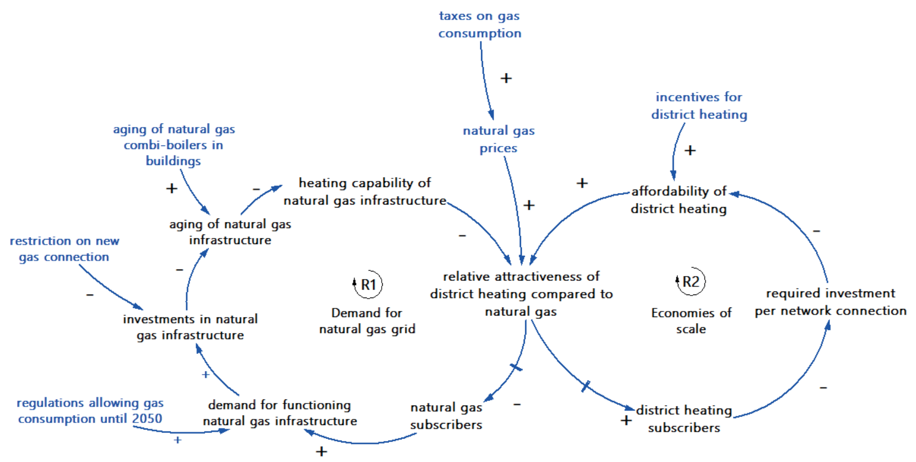

Figure 4 - National policy of the Netherlands to replace natural gas in the built environment, represented by two reinforcing feedback loops R1 and R2.

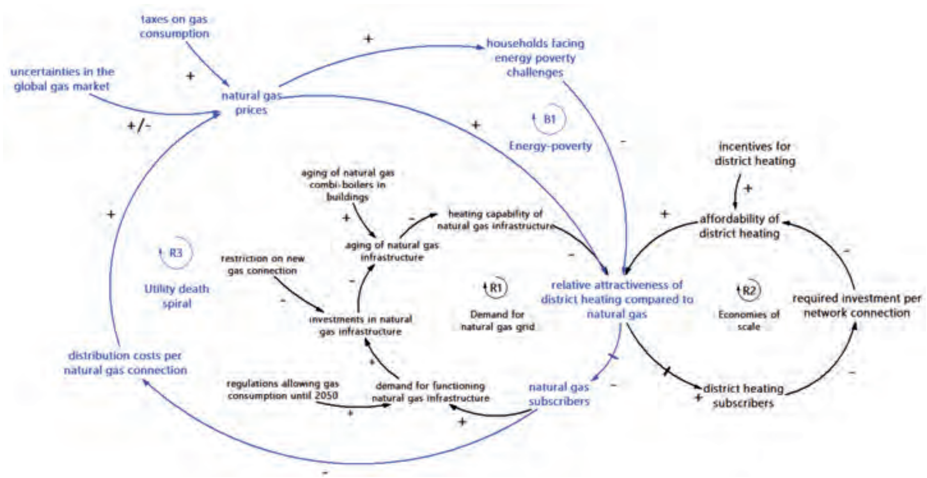

Figure 5 - Energy-poverty caused by increasing natural gas prices can obstruct the transition out of gas.

natural gas customers and revenue to achieve carbon-neutral cities which puts a time pressure on energy companies to diversify their heat sources. Dutch energy companies could face losses as maintenance costs stay the same while the natural gas market shrinks over time. Such repercussions have been recently discussed for the electricity sector, as energy companies have experienced substantial losses due to the high-penetration of solar panels [56]. This mechanism can implicate a potential utility death spiral [57] for the heating sector. Two reinforcing feedback loops, namely **R2** and **R3**, jointly work against natural gas and in favor of district heating systems: a higher adoption of district heating systems leads to higher distribution costs for natural gas. In turn, this accelerates the switch out of natural gas, leading to even higher distribution costs for natural gas.

Energy poverty is a term for not being able to afford energy prices, use a desired level of energy, and/or improve the occupied house's efficiency due to financial challenges [54]. Households with energy-poverty challenges need financial and organizational support to replace natural gas with an alternative heating system. Energy-poor households will be impacted disproportionately by increasing natural gas prices due to their energy-inefficient homes, which leads to higher taxes for higher levels of consumption. Consequently, energy-poor households will be forced to pay a higher share of their income for their heating needs, further reducing their financial capability to replace natural gas, as shown in **B1**. Although increasing gas prices (**R3**) accelerate the transition away from natural gas, energy poverty (**B1**) will counteract and limit this beneficial effect, prolonging natural gas consumption. Unless incentivized, households with energy poverty challenges might be dependent on their existing gas equipment/system longer than desired, leaving them vulnerable to uncertainties/increases in natural gas prices, and at risk of experiencing further energy poverty.

Urban strategy for an inclusive transition

Starting the energy transition in the social housing sector can hit two birds with one stone: activating economies of scale for the district heating system and achieving an inclusive energy transition for households with energy-poverty challenges [51]. The Netherlands has one of the highest ratios of social housing in Europe, with four million citizens (out of the seventeen million) living in social housing. Housing associations hold 31.5% of the market share in the housing sector [58]. In the project locations, 60% of the residents live in social housing. To switch out of natural gas, Dutch municipalities normally opt for a neighborhood-by-neighborhood transition plan, beginning with areas that have a high concentration of social housing complexes [5]. **Figure 6** shows the policy to accelerate the transition away from natural gas towards district heating.

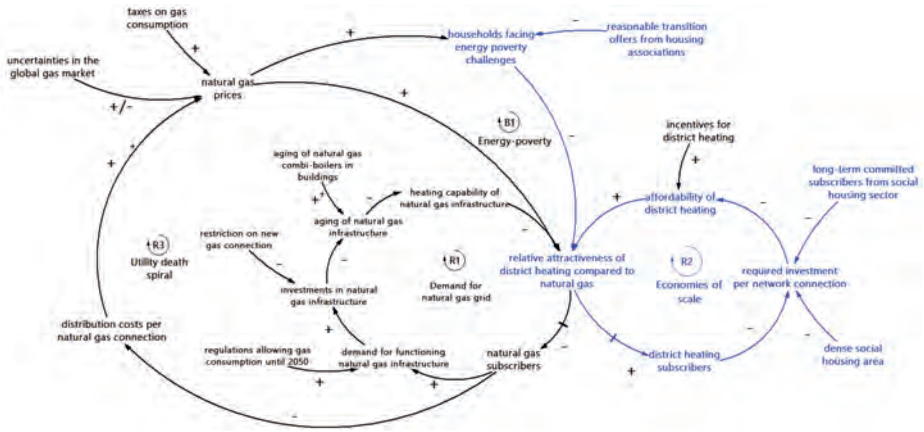

Figure 6 - Housing associations accelerate the adoption of district heating systems.

The collaboration with housing associations reinforces the benefits from economies of scale in district heating, forming an addition to **R2** in **Figure 6**. In dense social housing areas, network operators can guarantee sufficient connections to achieve an attractive business case for their investments. Committed and long-term subscription from social housing also improves the cash-flow profile of the heat network and loan/subsidy acquiring capabilities for the network operators and heat producers [52]. Furthermore, social housing complexes have relatively uniform natural gas equipment and heating requirements; hence, they allow for more scale efficiencies, as opposed to private buildings that often have diverse technical equipment and heating requirements. The shared renovation moments in social housing areas can be leveraged to encourage the expansion of the heat network. By starting the transition in the social housing sector Dutch municipalities expect to replace gas in sizeable street/neighborhood-wide projects and subsequently scale up the heat network.

Starting the urban transition in the social housing sector is considered easier than through an incentive-oriented set of municipal policies aimed to convince private homeowners and renters who might have a wide range of social, economic, and cultural backgrounds with different heating requirements [51]. However, residents in social housing have lower economic power compared to the national average since they have to be financially eligible to live in the rent-controlled and subsidized houses [59]. In the Netherlands, 75% of the energy-poor households live in social housing [54]. Often, energy-poor households have other financial priorities than mitigation. Housing associations collaborate with municipalities and energy companies to organize and manage the transition in the social housing sector. Thus, they are in a position to reduce the obstructing effect of energy poverty (**B1**) and reinforce the beneficial effect of economies of scale (**R2**).

Two-phase no-regret transition

Rotterdam opts for a no-regret transition: first scaling up the existing heat network that uses a high-temperature regime, and then switching to a medium-temperature network when energy-efficiency requirements are met [46]. A no-regret transition can be defined as switching to an energy system which is financially and technically applicable, supports climate-mitigation efforts, generates societal benefits (e.g. energy security, energy justice), and has the resilience and flexibility for the next steps of the energy transition [60]. The current plan in Rotterdam seems to fit all criteria. First, a high-temperature network does not require investments/refurbishments for energy efficiency at this stage. This offers an inclusive option for older buildings in which energy-poor households often live. Hence, focusing on the expansion of the network would allow more citizens to replace natural gas. Correspondingly, an interconnected high-temperature network in the Randstad region can significantly contribute towards achieving the urban emission mitigation goals by 2030 [46,61] because there is an abundant supply of high-temperature heat available in the port of Rotterdam [62]. Finally, the grid components (e.g. pipes, substations) can be designed to accommodate both high- and medium-temperature regimes [46]. Therefore, the same network can be used as a foundation towards low-carbon heating systems when the built environment is well insulated. Similar to the other cities with existing heat networks, Rotterdam aims to first scale up and expand the heat network to substitute the natural gas connections at buildings, then reduce the temperature of the network through energy-efficiency investments/refurbishments, and, finally, develop and integrate the available renewable heating systems in the region.

First phase: expanding the network

Figure 7 demonstrates the first phase of the no-regret transition: the expansion of the heat network. District heating networks offer a scalable urban heating system for the future because they can integrate multiple central heating systems to satisfy the high-volume demand of the city. One of the most complex tasks is to match supply and demand in district heating systems in growing networks [63]. Notably, heat networks and central heating systems depend on each other's success. As more citizens start using district heating, the heat demand of the network increases, which requires an expansion of the heat production capacity. This creates a reinforcing effect on heat production as shown in **R4**. Similarly, an increase in heat production capacity creates demand for the distribution of heat to customers, creating a reinforcing effect on the heat network. These two reinforcing effects can also work the opposite way: the expansion of the heat network can be halted unless there are heat sources, or vice versa. Therefore, it is safe to say that district heating networks and central alternative heat sources co-develop (or co-decline) to substitute for the natural gas in urban heating.

This synergy between heat networks and central heating systems leads to both economies of scale [64] and scope [65]. To clarify the economies of scale: a single heat network can connect numerous heat sources and buildings. As heat distribution and production capacity increase in tandem, the expenses associated with infrastructure and inputs (e.g. investments, fuel, and maintenance) are divided among a larger number of users [52], resulting in a decrease in the cost of heat per network connection. As to the economies of scope, adding more central heating systems to the network leads to several benefits: increased energy security [66,67], improved system flexibility [4,68], reduced fuel consumption and energy costs [69], and the integration/utilization of renewable heating systems [70,71]. Consequently, co-development of the heat network and heat sources reinforces the financial advantages for citizens, heat producers, and network operators and thus accelerates the transition out of natural gas in the built environment. This synergy is one of the main reasons why the district heating system is the most affordable option in dense built environments where there is an existing network or a heat source nearby.

Second phase: energy-efficiency and renewable integration

Figure 8 explains the second phase of the transition plan: carbon-neutral heating. There are several prerequisites to achieving this goal. First, energy-inefficient buildings need to be refurbished to make the city ready for low-temperature heating. In the Netherlands, the National Insulation Program [72] aims to incentivize thermal insulation in the urban environment to decrease dependency on natural gas and open up the pathways for low-carbon heating solutions in the future. Property owners, including housing associations, are incentivized to insulate their buildings before 2030. **R5** shows that incentives and regulations motivate investments in energy efficiency, reducing the heat demand of the buildings and heat network.

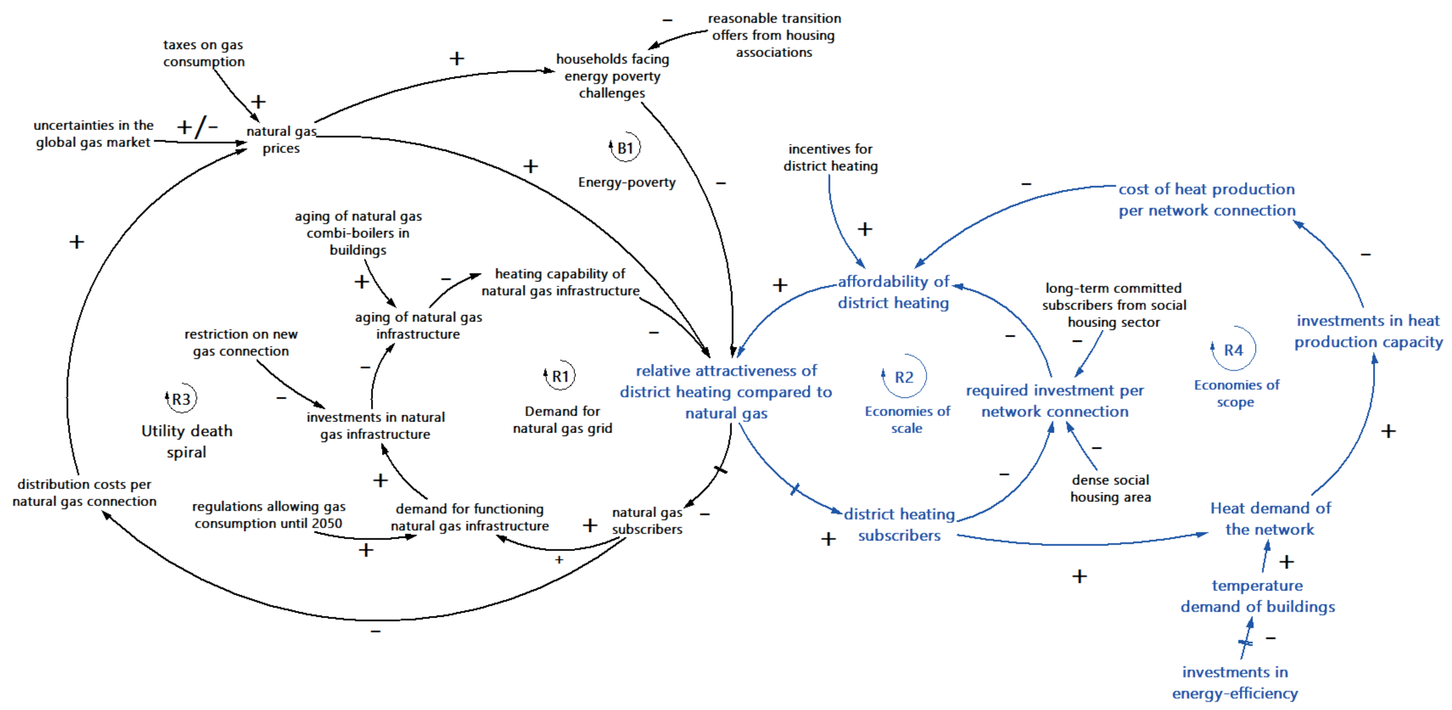

Figure 7 - The first phase of the transition plan: the expansion of the heat network.

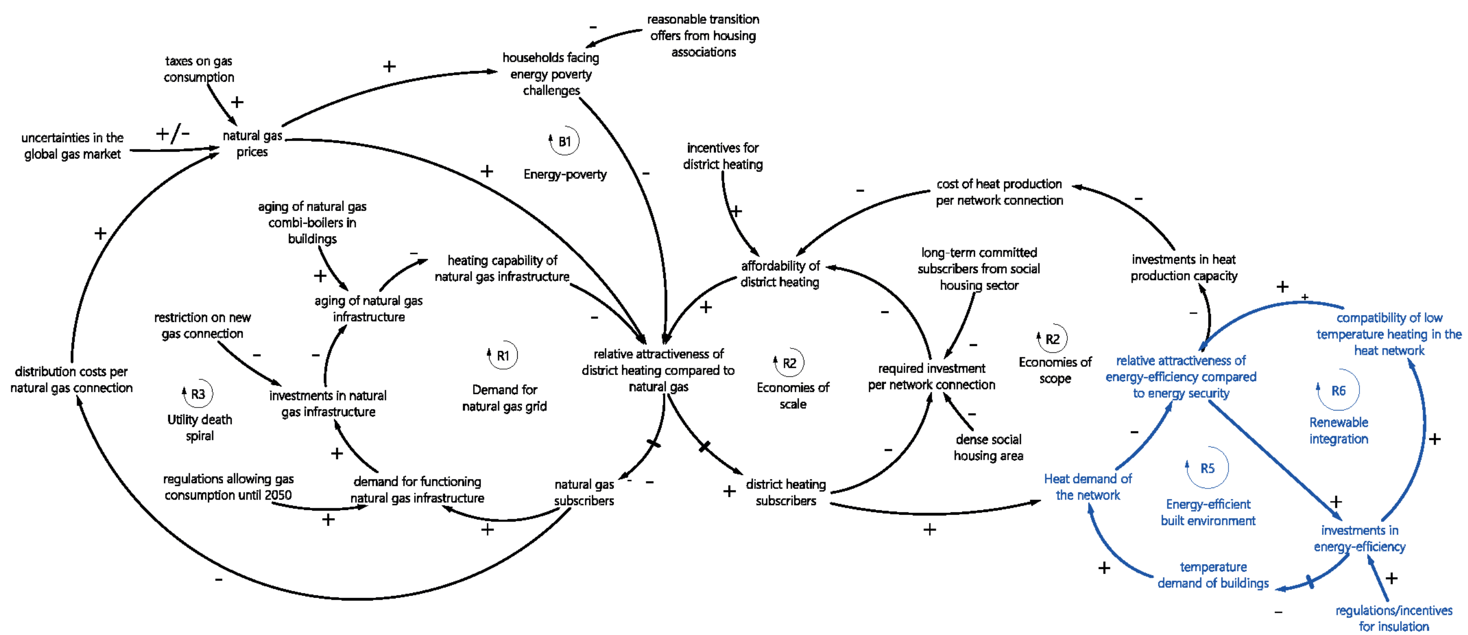

Figure 8 - The second phase of the transition plan: low carbon heating.

Low-carbon central heating systems need to be developed in tandem with energy-efficiency investments. Medium-temperature networks cannot use a high temperature heat source (e.g. residual heat, waste-to-energy) in an efficient manner [73]. The buildings in the city need to be insulated to allow the integration and utilization of renewable heating systems, as shown in **R6**. The city of Rotterdam plans to invest especially in geothermal and aquathermal systems [46]. Geothermal energy is one of the heating alternatives that can deliver high-, medium-, and low-temperature regime water to the heat network[5] [74], which fits current transition plans. At present, there are numerous plans and projects for geothermal development which can supply high-temperature water to Rotterdam's heat network [75]. Aquathermal systems are low-temperature heating systems that can be used in the future when the buildings are energy-efficient and the heat network is ready for a lower temperature. There have been small-scale and stand-alone (detached from the heat network) aquathermal projects as proofs of concept [76,77]. As more low/medium-temperature heating systems develop, the plan is to integrate them in the existing heat network to reduce the fuel consumption of the network and energy costs of the city [68].

The main premise of the plan is to reinforce the expansion of the heat network and production first, increase the energy-efficiency of the network, and invest in and utilize low-carbon heating systems[6]. Notably, focusing on a two-phased transition can significantly mitigate emissions leading up to 2030. However, **Figure 8** shows that these two plan phases and the policies which are employed in these phases actually work against each other by triggering a competition between scaling up the heat network (energy security) and lowering the heat demand of the city and network to allow the coupling of low-carbon systems (energy efficiency). Since energy security has more immediate consequences on societal (in)equality, it is likely the expansion of the heat network and heat production will be prioritized over energy efficiency and renewable integration in the built environment. If unchecked, the expansion-first strategy could displace investments from low-carbon heating in the built environment, worsen energy poverty for significant groups of citizens, and prolong the use of carbon-heavy heating systems.

A systemic trap during the no-regret transition: dependency on carbon-heavy systems

Heat network operators in the Netherlands are mostly energy companies which already own natural gas distribution rights for several urban regions [78] and deliver high-temperature heat that relies mainly on carbon-heavy sources [13]. These energy companies compete in municipal bids for long-term heat distribution rights before deploying the necessary infrastructure, in this case the heat network and heat sources. **Figure 9** shows the consequences of long-term contracts involving available heat sources.

On the one hand, long-term contracts ensure network operators to function over the lifespan of the infrastructure investment [79,80] and thus minimize the chance of stranded assets or sunken costs while replacing natural gas [81]. Network operators can earn their investments back over a long time period while ensuring continuous stable income and affordable monthly tariffs [52]. On the other hand, available heat sources are typically carbon-heavy and rely on fossils [13]. Residual heat is a prominent carbon-heavy yet energy-efficient alternative for the near future [49], because it utilizes a previously untapped energy from industrial processes [82]. Notably, the port of Rotterdam is the largest seaport of Europe where many petro-chemical and energy companies are located [45]. The residual heat from the port can be scaled up at limited costs [62] compared to other alternatives. Similarly, the proposed waste-to-energy system is another carbon-heavy yet energy-efficient alternative [83]; however, this option would be limited in the future due to supply scarcity challenges for municipal waste [84]. Hence, natural gas can be used to supply heat to district heating systems as back-up or peak-demand, as this option still produces less emissions compared to boilers at buildings. As all available heat sources are carbon-heavy at this stage, long-term contracts based on these sources would prolong the use of carbon-heavy heating in the built environment. It is important to note that these carbon-heavy systems would eventually be commissioned out or coupled with CCS [5,85] to achieve carbon-neutral cities.

Over-investments in carbon-heavy systems could lead to a dependency on CCS which could crowd-out investments towards energy efficiency and low-carbon heating systems [5]. Redesigning the heat network with a low/medium-temperature regime may require significant new investments, lead to stranded assets and contract breaches for high-temperature systems [29,81], or simply be postponed until long-term contracts end, leading to continued dependence on carbon-heavy solutions coupled with CCS. Interestingly, **Figure 9** shows that the dependency on CCS (**R7**) reinforces the expansion of the heat network (**R4**). To clarify, the dependency on available carbon-heavy heating systems could motivate further investments in CCS which can further delay investments in energy efficiency and renewable integration. In other words, underdeveloped low-carbon alternatives and energy-inefficient built environments may further justify increasing the heat production capacity with carbon-heavy systems, including fossils. Unless there is a concrete plan for each carbon-heavy heating system, the heat network could very well expand to cover the whole city and satisfy the urban heat demand securely,

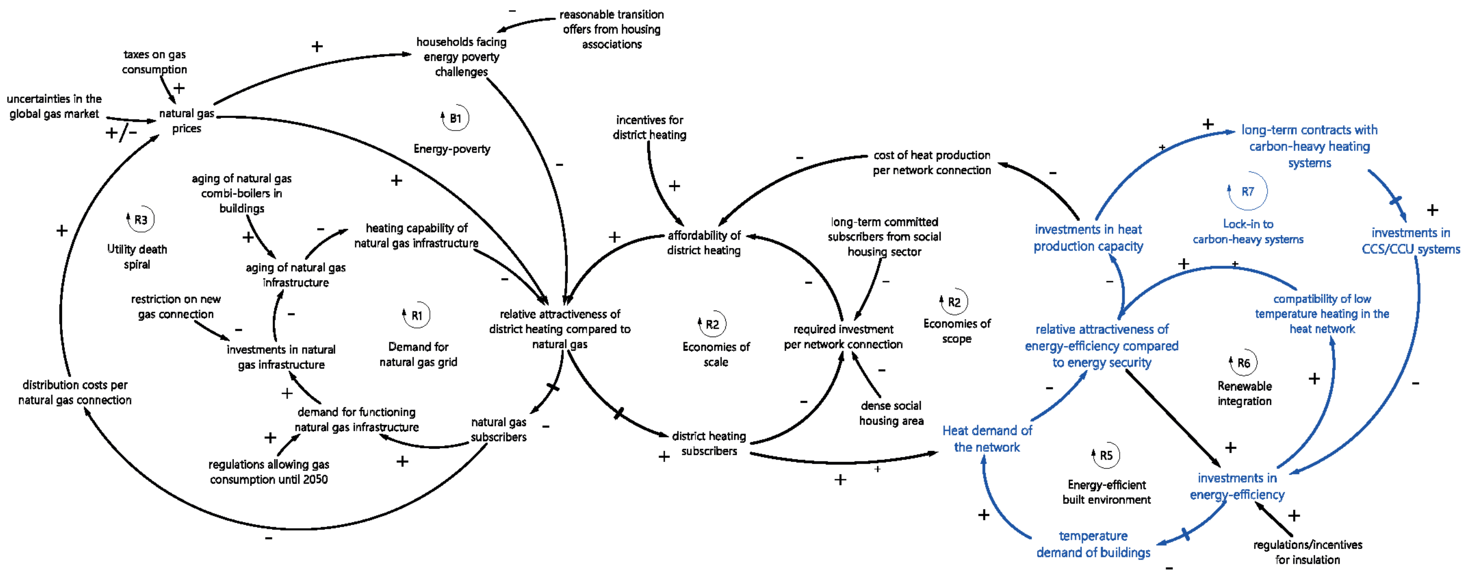

Figure 9 - A systemic trap during the no-regret transition: dependency on carbon-heavy systems.

at the cost of prolonging the dependency on carbon-heavy heating and CCS, and of limiting the pathways towards renewable heating in cities.

Discussion

The city of Rotterdam currently plans to expand the existing heat network first. This high-temperature network, according to current policies and plans, will function as a bridge to the medium-temperature network in the future. Without leveraging this affordable and technically feasible pathway, carbon-neutral heating in Dutch cities might be delayed due to higher costs and technical challenges for alternative heating systems. The current urban strategy and national regulations can help the adoption of district heating while impeding the consumption and incorporation of natural gas in Dutch cities. Furthermore, a timely deployment of thermal insulation and low-carbon heating systems could accelerate the emission reduction efforts in Dutch cities. On the other hand, socio-technical interdependencies may initiate mechanisms that could also hinder or delay the transition towards carbon-neutral heating unless they are well-considered and governed by decision-makers [19,86].

In this paper, we utilized causal loop diagrams and participative modeling to structure and demonstrate socio-technical interdependencies that can either help or hinder the realization of carbon-neutral heating in Rotterdam. Building models of feedback structures can help researchers and decision-makers to differentiate overlapping and counteracting influences of various energy policies on urban energy systems and assess its long-term consequences on climate policy. System models can help structure and manage the complexity while governing urban energy transitions. They can be utilized during urban co-creation processes to identify high-impact systemic effects and thus initiate an open dialogue between impacted regime actors, cross-sectoral experts, and policy domains. **Figure 10** summarizes the mechanisms that result from socio-technical interdependencies in Rotterdam. Our findings have implications for the transition governance literature and Dutch climate policies.

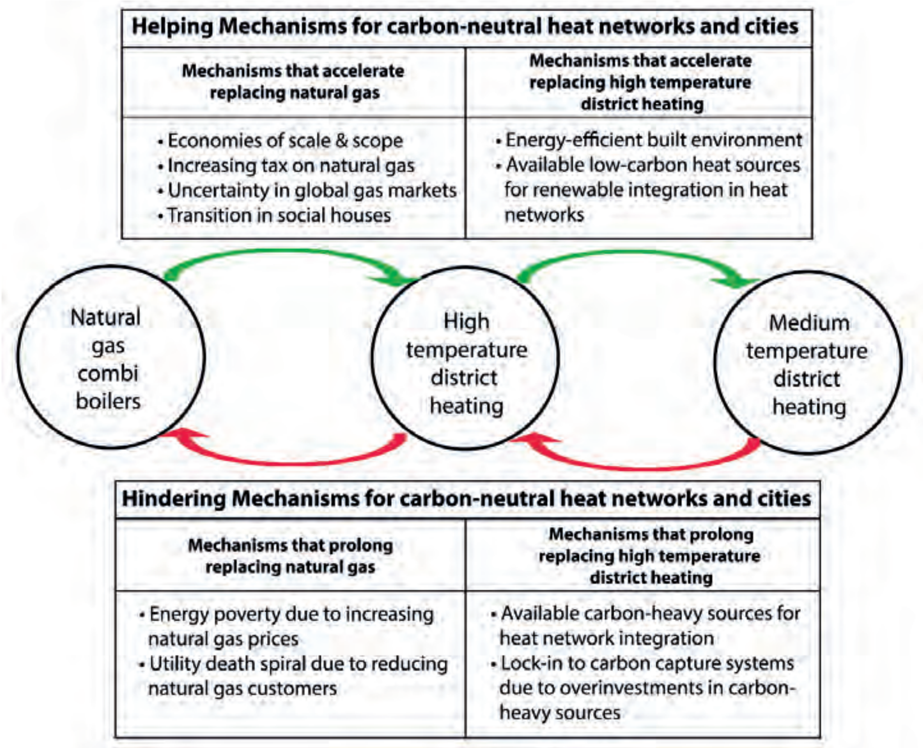

Figure 10 - Helping and hindering mechanisms for achieving carbon neutral cities with district heating systems.

Transition governance

Achieving carbon-neutral heating in cities will depend on whether the interdependent mechanisms align and support the planned technological trajectory [87] towards low-carbon heating systems instead of carbon-heavy ones. If hindering mechanisms become more dominant, climate policies can encounter resistance [39]. The landscape elements in Rotterdam, specifically existing heat network and notably available carbon-heavy heat sources, create a significant window of opportunity to switch out of individual natural gas heating to another mature heating system - high-temperature district heating systems [17]. From a technological point of view, a high-temperature network can be used as a bridge towards a developing niche energy system in the future - low-temperature networks. However, regime actors, in this case policy-makers and energy companies, are often responsible of a range of societal goals which can be indirectly inconsistent with each other [88,89]. To illustrate this, prioritizing the expansion of heat network over energy efficiency, could result in continued investments in carbon-heavy sources, including fossils, to accommodate the high-volume demand from the heat network. The exploitation of carbon-heavy sources could be prolonged which could lead to a dependency on CCS in the heating sector and displace investments from energy efficiency and renewable heating. Subsequently, urban emissions could decrease significantly at first as social housing-heavy areas of cities transition to district heating but could stagnate when the residual urban heat demand cannot be matched [13] by low-carbon heat sources. At that stage, regime actors would have the legitimacy to keep investing in heavy-carbon sources to ensure energy security but delay investments in low-carbon heating which is necessary for carbon-neutral cities.

Overall, the energy systems change as a response to the accumulation of interconnected (helping and hindering) feedback mechanisms. In other words, the urban energy transition ultimately depends on which of these mechanisms are most dominant. Qualitative models can show leverage points and consequential feedback structures to consider in future decisions and policies [90]. Overcoming potential traps on the way to carbon-neutral cities requires synthesizing pieces of interdisciplinary information encompassing interactions in urban socio-technical systems. One of the causes of policy resistance is that climate policies are often decided and developed in relative isolation from each other in different decision-making arenas; thus, the resulting policies could overlook these complex interconnections.

Consequently, there have been calls for multi-level governance in urban transitions [91,92] and discussions on how adopted policies could indirectly affect each other [88]. At the heart of these discussions, researchers signal that the influence and reach of a policy is “modified by the existence of other policies” [93]. Participatory decision-making approaches, discussed under the co-creation literature [94–96], could be a prominent method to identify interdependencies and ensure communication and collaboration between policy-makers and decision-making bodies to explore possibilities for policy alignment and thus to overcome policy resistance [88]. Of these approaches, GMB [11,25] can support co-creation processes. It can support researchers and decision-makers to structure the complexity in the (re) design of socio-technical systems [25] and reveal (in)consistencies between policies and urban dynamics. Resulting models can highlight the interdependencies and their impacts on regime actors, cross-sectoral experts, and policy domains. By identifying interdependencies, researchers can highlight which stakeholders should be involved in decisions and which policies might require more coordination to realize the transition. We propose the use of qualitative models and participative modelling as a useful preliminary step during co-creation processes [94–96] to identify systemic consequences and interdependent stakeholders. Thereby, we aim to engage an open dialogue between decision-makers, cross-sectoral experts, and citizens with a list of interesting dynamics to initiate and facilitate discussions in future co-creation steps [12].

Policy implications

Lessons from Rotterdam can apply to other cities in the Netherlands. Dutch cities with district heating [13] offer an affordable heating opportunity as compared to other alternatives [97] and a significant emission reduction when deployed [98]. Hence, expanding these existing district heating networks could potentially benefit both citizens and climate goals, while also providing a flexible system which can be combined with today's carbon-heavy but significantly more efficient heating systems and with tomorrow's low-carbon heating systems.

To prevent delays in the substitution of natural gas, the Netherlands supports households with economic measures while also addressing energy poverty through subsidies and affordable long-term loans [54]. As the first policy suggestion, taxes on natural gas consumption could be directed in a governmental fund to be used towards helping households deal with the challenges of substituting natural gas. On the city-level, the Rotterdam municipality scouts the urban environment for locations where a switch towards district heating represents the best opportunity. The municipality frequently organizes planning meetings with energy companies, infrastructure service providers, housing associations, and citizens to realize district heating projects [46]. This collaboration is important to realize acceptable terms for citizens in social housing.

Finally, a concrete exit strategy for high-temperature heating systems could prevent prolonged use of carbon-heavy heating systems in cities [6]. For each prospective urban heating system, this exit strategy should include at least the maximum allowed capacity, return on investment period, possibility of stranded assets, profitability of developers, costs of utility prices, and carbon price over time. This roadmap for carbon-neutral heating should discuss supply and demand (mis) match in the urban heating system and the time window for insulating the build environment. Each city should create its own exit strategies tailored to the local dynamics. Moreover, escalating carbon pricing for both captured and uncaptured carbon could dissuade developers from heavily investing in carbon-heavy compatible systems. The proceeds from carbon pricing could be used to incentivize low-carbon systems, instead of CCS, which could pique the interest of energy companies to deploy low-carbon systems sooner.

Limitations

In this study, we utilized qualitative models to discuss the effects of socio-technical interdependencies during urban energy transitions. Qualitative models can be powerful tools in scoping the relevant boundary and influential elements within complex systems such as urban heating systems. However, our results cannot make claims about which feedback mechanism will be the deciding factor in the system behavior, or whether other cities with district heating systems will be impacted in the same manner as Rotterdam [31]. Hence, quantifying and building simulation models to reveal the dynamic changes in different urban energy transitions could build on the qualitative insights from this study [6,99].

Qualitative models can embed contrasting views on urban transitions from different stakeholders and data sources. Evidently, these models also reflect the perceptions and biases of the research participants and reviewed documents. This paper focused on prospective policies with a limited number of stakeholders regarding the switch from natural gas to district heating in Rotterdam which is part of an ongoing transition project. Investigating the same system with different boundary assumptions (e.g. other heating technologies, other cities) and extending the participant and data pool can reveal novel insights and perceptions on potential interdependent mechanisms beyond those discussed in this study.

Conclusions

This study set out to explore and discuss socio-technical interdependencies that can help or hinder urban energy transitions. To achieve that, we used participative modeling techniques and qualitative SD models to show the interdependencies in the urban socio-technical system as well as the policy-resistance mechanisms towards carbon-neutral cities. District heating systems can be leveraged to accelerate the switch away from natural gas heating in Dutch cities as part of current national and urban strategies. Nevertheless, there could be indirect consequences, or systemic traps, that researchers and policy-makers should take into account. Unless interdependencies are understood and managed, climate efforts could be met with policy resistance, one prominent example being the dynamic rivalry between energy security and energy–efficiency policies. We conclude that considering interdependencies in urban decisions could support co-creation processes, reduce policy resistance, and prevent delays and bottlenecks in energy transitions. Resulting models summarize the lessons learned and embody our answer to the research question.

To achieve carbon-neutral cities, carbon mitigation and energy security must go hand in hand. At its core, the energy transition is about changing every human being's social, economic, and cultural conditions and behaviors to allow for a technological change in the energy system. This is not a simple goal because the interdependencies between technology and society are constantly redefined during urban transitions. Ensuring a carbon-neutral future requires an interdisciplinary perspective to synthesize the crucial knowledge from cross-sectoral experts as well as acting on this synthesized knowledge in open and collaborative co-creation processes.

Footnotes

1. We have searched the Web of Science database to look for papers that included "interdependen*", "system dynamics", "socio-technical", and "energy". We could not find any papers. Then, we broadened our research to "interdependen*", "systems approach", "socio-technical", and "energy" & "interdependen*", "systems thinking", "socio-technical", and "energy". This resulted in 4 papers [100–103] that utilize systems approaches but that do not focus on the heating sector. Next, we expanded our search string to "energy" & "interdependen*", "system", "socio-technical", and "energy", still resulting in only 16 papers. These articles often mentioned the importance of systems approaches/thinking without utilizing any of the conforming analysis methods.
2. **Table 1 -** Qualitative data collected by the research participants

Responsibility	Organization	Type of organization	Semi-structured interviews	Expert-specific interviews	Workshop 1	Workshop 2
Advisor & Project expert	Rotterdam Municipality	Government	x		x	x
Urban designer	Rotterdam Municipality	Government		x	x	x
Climate adaptation	Rotterdam Municipality	Government		x	x	x
Area manager	Rotterdam Municipality	Government			x	
Urban development	Rotterdam Municipality	Government			x	
Financial advisor	Rotterdam Municipality	Government			x	
Neighborhood manager	Rotterdam Municipality	Government			x	x
Neighborhood manager	Rotterdam Municipality	Government			x	
Sustainability manager	Woonstad	Housing association	x		x	x
Sustainability manager	Havensteder	Housing association				x
Account manager	Stedin	Grid operator		x	x	x
Project expert	Eneco	Energy company		x	x	x
Technical expert	Eneco	Energy company		x	x	x
Transition consultant	Infram	Consultant		x	x	x
Transition consultant	Infram	Consultant		x	x	x
			2	7	14	11

3. See [4,104] for more information on third- and fourth-generation district heating systems. Scandinavian countries have been discussed as being the most progressive when it comes to district heating systems [4,105,106]. The Netherlands has been motivated by these success stories, passing the so-called Heat Act 2.0, which underpins the co-ownership of district heating systems similar to examples in Scandinavian countries [107]. The state of the district heating systems in the Netherlands is described in reports [13,108].
4. A city-scale heat pump transition will result in demand spikes during wintertime, with significant implications for the electricity grid. Such fluctuations in customer demand make it challenging to further integrate renewables in the electricity sector [109], which has also been observed in the Netherlands [110]. However, heat pumps can still be very relevant for buildings with technical challenges that prevent a heat network connection, or for wealthier and environmentally conscious households [111]. As a result, the city of Rotterdam intends to utilize district heating systems where available since it is one of the most cost-effective and scalable heating alternatives for these neighborhoods [46].
5. Notably, the investment costs of geothermal systems are almost three times higher, while operational costs are 50% higher than residual heat [97]. Furthermore, achieving a high-temperature regime with geothermal energy requires deeper wells and thus higher investments. 40% of the geothermal investment costs come from the well-drilling and field development activities [112], and the costs of geothermal wells increase exponentially as the depth of the well increases [113]. All things considered, geothermal investment costs are relatively high to be earned back in the heat market [97], compared to residual heat or waste-to-energy plants (e.g. plants using municipal waste).
6. Below we outline the feedback loops that represent the discussed mechanisms.

   First phase:
   (R2) Expansion of the heat network
   (R4) Expansion of the heating system
   Second phase:
   (R5) Investments in the energy-efficiency of the network
   (R6) investing in and utilizing low-carbon heating systems

Figure 8 shows that these two phases (namely R2 & R4 vs. R5 & R6) can work against each other and lead to a competition between scaling up the heat network whilst securely satisfying the urban heat demand (R2 & R4) versus lowering the urban heat demand and temperature of the network to allow coupling of renewable heating systems (R5 & R6).

Appendices

Appendix A - Data collection methods

We prepared an accompanying Mendeley data folder where we provide further details about the chosen methods, their limitations, the Rotterdam case, qualitative data, coding approach, workshop reports, resulting system models, and research collaborators. The data folder can be reached via the following DOI:

Gürsan, Cem (2024), "District heating with complexity: Anticipating unintended consequences in the transition towards a climate-neutral city in the Netherlands", Mendeley Data, V5, doi: 10.17632/f8nwdjvhpf.5

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Chapter 5

Feedbacks in energy transition governance: A systems analysis of European district heating policies

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The final chapter opted for a broad analysis scope for energy transitions in accordance with suggestions from previous chapters to answer the implications of feedback effects on energy transitions and their governance. A revised version of this research article is currently under consideration for publication at the Energy Reports journal and is co-authored by Dr. Mark de Bruijne and Dr. Vincent de Gooyert. The revised version of the article explores the implications for Europe in detail as suggested by journal editor and reviewers, whereas this original chapter explores the nature and potential behaviors of feedback effects in energy systems and transition policies.

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Abstract

District heating systems are considered a feasible heating alternative to replace natural gas 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 mechanisms. The objective of this study is to increase knowledge on the implications of feedback effects in transition governance by highlighting how they can lead to unexpected systemic consequences, thereby causing inertia or acceleration during transitions to district heating systems from natural gas. 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 policy-makers 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 mechanisms. Unless feedback effects in transitions are acknowledged by policy-makers, they could work against carbon-neutrality targets due to wrong assumptions and prioritizations of inconsistent policy sub-goals. Therefore, policymakers need to recognize and comprehend how feedback mechanisms between energy systems and policies are formed and operate.

Keywords
Transition Governance; District Heating Systems; Feedback Effects; Co-evolution

Introduction

In Europe, heating and cooling are roughly responsible for half of the total energy consumption and 36% of energy-related emissions [1]. Thus, they constitute a significant part of the emission volumes of cities [2]. One of the main causes of this poor performance is the pervasiveness of natural gas-fired boilers in the urban heating sector [3]. Working towards a net-zero future requires replacing these boilers with alternative heating systems that do not rely on fossil fuels across Europe.

District heating systems, along with other alternatives[1], are considered feasible substitutes of natural gas heating systems because they represent a cost-effective alternative for dense European cities [4,5]. These systems utilize combined heat-and-power plants (CHP) and residual heat to increase energy efficiency and reduce fuel consumption [6,7]. This form of heating can integrate power, heat, thermal storage, and smart systems to increase the energy efficiency [8,9], and scale up the utilization of renewables to mitigate emissions [10,11]. The Renewable Energy Directive, which is the legal framework for clean energy in EU countries, stresses the importance of taking prompt action to substitute natural gas heating with (more) sustainable options and considers district heating systems as a significant component of net-zero cities towards 2050 [12]. Although many European countries recognize district heating systems as feasible alternatives and are implementing various policies to stimulate their use, the adoption and utilization of these systems vary notably across the continent [13]. Apart from geographic considerations, this variance can be accredited to social and technical differences between national contexts [14].

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 disruptions/changes [15]. Interdependencies have the potential to transcend the boundaries of technologies, sectors, markets, policies, cities, and even countries [16] which may result in so-called feedback effects. Feedbacks occur when interdependent elements in (socio-technical) systems influence each other through a closed chain of causalities, and in turn, themselves [17]. Due to the complexity and sheer magnitude of the energy transition challenges, feedback effects can remain hidden and go unnoticed by policy-makers [18], leading to various indirect, and often unexpected, systemic consequences [14] that could accelerate or hinder energy transitions [19]. For example, the recent surge of investments in coal power production across Europe has been discussed as a potential consequence of feedback mechanisms (even before the current disruptions to the global natural gas supply chain) [20].

The transition governance literature [21] highlights the continuous systemic interactions between public policies, markets, societal norms, and technological systems [19] and how such feedback influences policy actors and their subsequent policy-making [22]. The presence of feedback effects implies co-evolution: policy-making shapes energy system developments which, in turn, influence policy-making through a range of feedback mechanisms [21].

This study aims to provide new insights into the implications of feedback effects on transition governance [21] by highlighting how they can lead to unexpected systemic consequences, thereby causing inertia or acceleration during transitions to district heating systems from natural gas [23,24]. 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: *What are the implications of feedback mechanisms on energy systems and transition policies that seek to substitute natural gas heating with district heating systems towards net-zero European cities?* To answer this question, we conduct a systematic literature review [25] on district heating systems and their governance in Europe. We analyze the collected data by developing qualitative system dynamics (SD) models [17] to study how interdependencies between energy systems and policies produce feedback mechanisms that can influence European district heating transitions and beyond. We draw conclusions about the complex nature of transitions towards net-zero cities in Europe and the implications of feedback on transition governance. Our results implicate that it is essential for policy-makers to recognize and comprehend how feedback mechanisms between energy systems and policies are formed and operate. Doing so can assist them in governing the (un)intended effects of subgoals and actor interests in energy transitions. While these subgoals and interests are indispensable for achieving net-zero cities, they are often indirectly in conflict with each other due to feedback mechanisms.

Theoretical background

District heating systems to replace fossils in urban heating

Figure 1[2] shows three components of district heating systems: demand, distribution, and production [26]. 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 are among the most cost-effective substitutes for natural gas heating systems in dense urban zones with cold climates [12,27], especially when the distance between heat production and heat demand is short [28]. District heating systems can integrate multiple heat sources which allow switching between fuels or technologies to increase efficiency during energy production [7,29] and to deal with peaks and fluctuations in heat production and/or demand [30]. Moreover, these systems can increase the system flexibility by integrating power, heat, thermal storage, and smart systems [31,32]. 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 [26]. Although district heating systems offer a significant potential for renewable integration and urban mitigation [33], their share in the European heating sector is only 12% [12]. Most of the district heating systems utilize high-carbon sources for their heat production [34]. Thus, the overall fuel mix in Europe is currently still dominated by fossils and other high-carbon sources (biomass and renewable/non-renewable waste) [35], thereby continuing emissions as depicted in **Figure 2** [27]. According to reports from the European Commission in 2021 [36], natural gas heating is the prevalent heating source except in a handful of countries which use either oil or renewables for space heating. However, 59% of these renewables are comprised of bioenergy alternatives [37] which are still high-carbon sources and are expected to face supply restrictions in the coming decades [38]. Researchers highlight that achieving net-zero cities with district heating systems calls for replacing the prevalent natural gas-heating, mitigating emissions from district heating systems by integrating renewable sources, and capturing/utilizing carbon from high-carbon heat production [27,39,40].

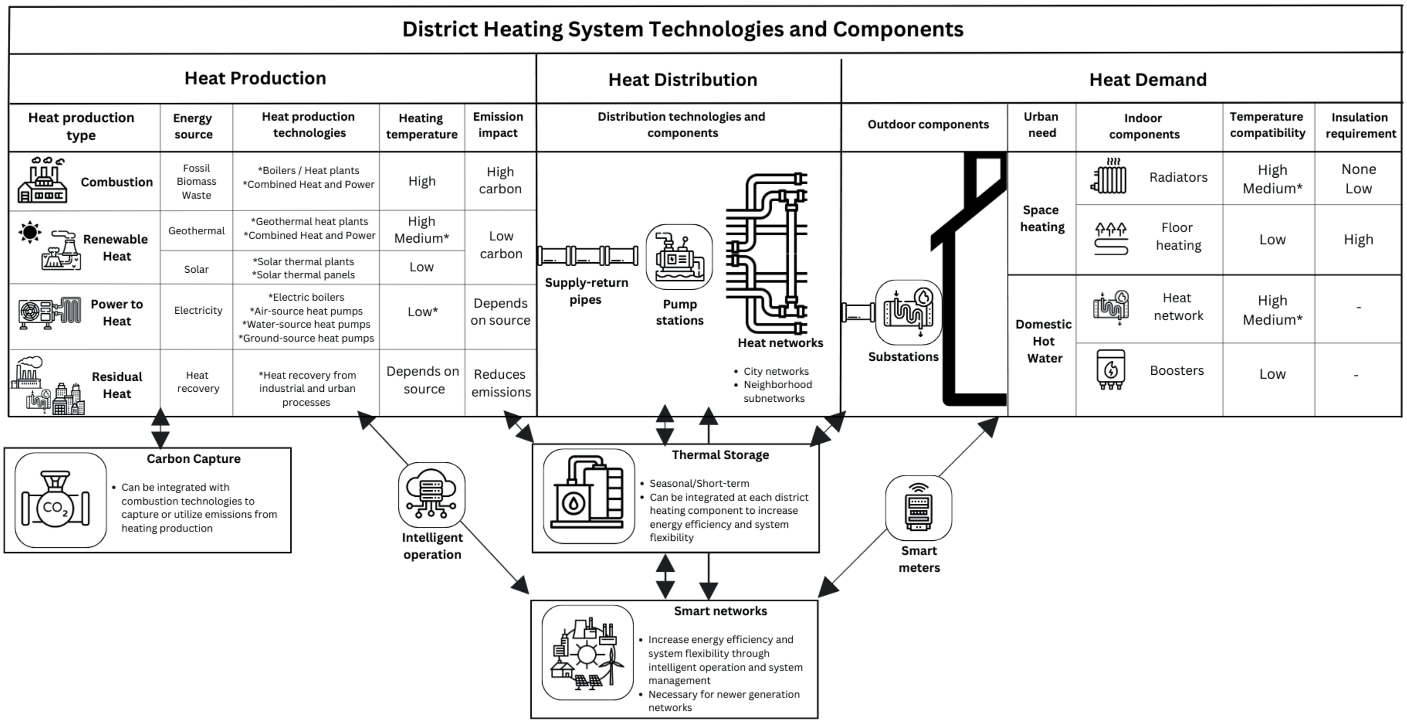


Figure 1 - Detailed representation of interconnected district heating components and technologies.

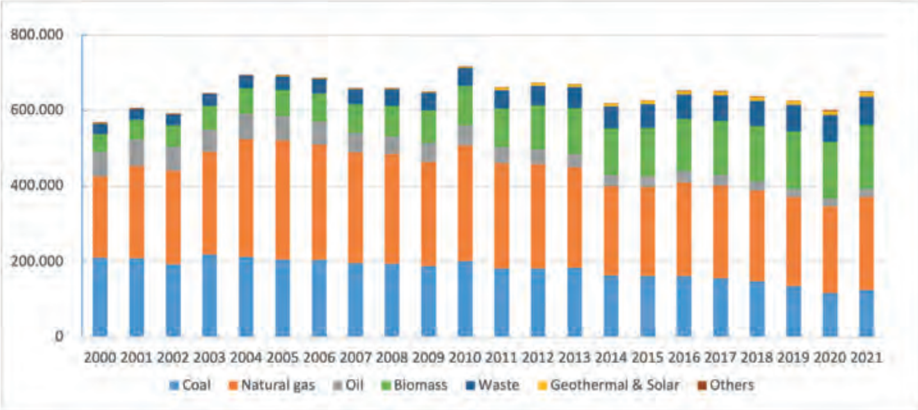


Figure 2a - Annual heat production (in GWh) by fuel source in Europe [35].

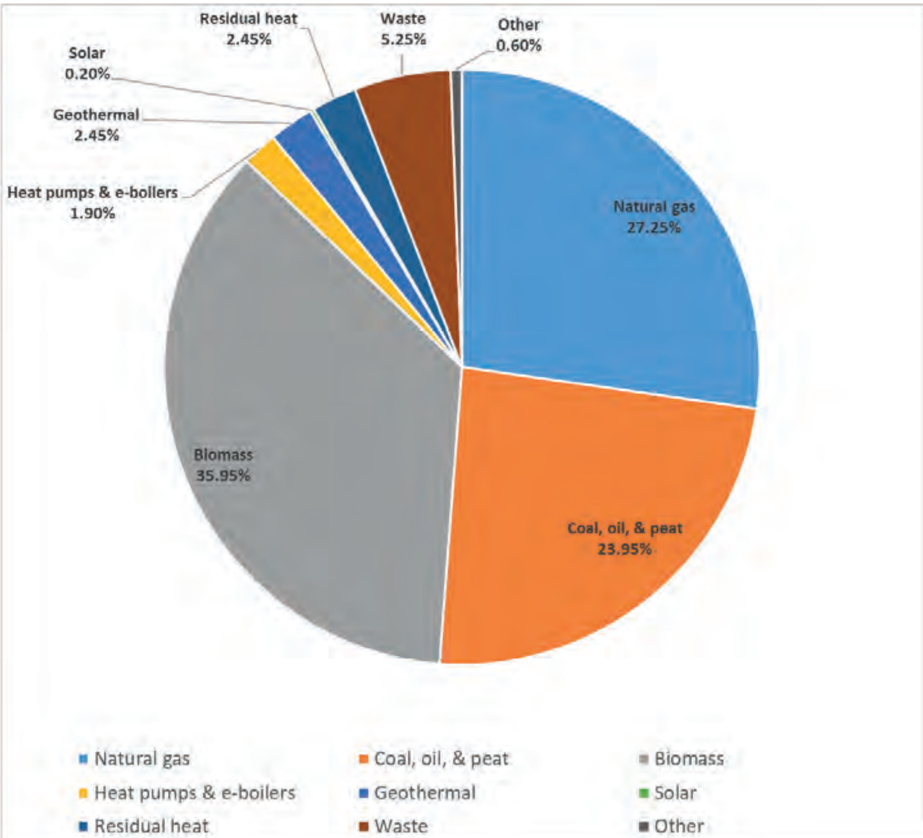


Figure 2b - Heat sources for district heating systems across Europe in 2021 [34].

Table 1 - District heating generations and technological innovations, adapted from [10, 27]

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°	Ultra High	Steam	* Heat plants (coal, waste) * Centralized thermal storage
2nd	1930-1980	> 100 C°	Ultra High - High	Pressurized hot-water	* Combined heat and power (coal, waste)
3rd	1980-Current	< 100 C°	High	Hot-water	* Combined heat and power (oil, gas, biomass) * Residual heat * Solar thermal plants
4th	2010-Current	< 70 C°	High - Medium	Hot-water	* Combined heat and power (waste) * Centralized heat pumps * Seasonal storage
5th	2020-current	< 40 C°	Low - Ultra Low	Hot-water	* Two-way heat/ cold transfers * Cold storage * Individual heat pumps * Individual thermal storage

Table 1 shows different generations of district heating technologies [10,26]. Over the years, they have become more efficient and moved to lower-temperature water regimes [41]. Third-generation networks are currently the most commonly found across the world and operate at temperature regimes below 100°C. They typically utilize combustion technologies for high-temperature heating (fossils, biomass, waste, etc.) [27] to satisfy the baseload heat demand; only a few integrate renewable heat sources to complement the heat production from high-carbon sources to mitigate emissions [42,43][3]. During the 1970s, third-generation networks became popular along with cogeneration systems[4], or CHP plants, to combat increasing oil prices which generated the incentive for efficient and affordable energy systems [44]. Newer generations operate at lower temperatures. This significantly reduces thermal losses during production and distribution, which increases the cost-effectiveness of heat networks [32]. Notably, fifth-generation networks can satisfy both urban heating and cooling demands by operating at ultra-low temperatures. They provide two-direction heat and cold transfers between each node [45]. Therefore, fifth-generation networks enable other heat and cold producers (data centers, solar thermal plants, etc.) and prosumers to feed into the grid, for example by selling

their excess energy back to the grid, which in turn increases the share of renewable generation in heat networks [41].

The choice to develop and build district heating generation is shaped by many contextual factors in the socio-technical system [14], such as available energy sources in the region, regulations/incentives for compatible heating systems, the distance between heat production and demand, available underground space, projections for the urban heat demand, and insulation level of the built environment. In turn, the generation choice also influences the socio-technical system [19] because it has systemic implications for the (future) compatibility of heating technologies[5], required piping diameters in networks and heating equipment in households, required energy efficiency levels in the system design and buildings, energy consumption/costs of the city, and so on. Such interdependencies can result in feedback between transition decisions and energy systems which may arise as path-dependencies during urban transitions [20].

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 [46,47]. In energy systems, path dependencies are generally characterized by incremental changes to maintain the quality and reliability of energy services [2]; thus, they are typically associated with inertia in policy-making that favors more mature and often polluting systems over emerging sustainable alternatives [48]. If path dependencies are overlooked, resulting policies could reinforce this inertia by (re)shaping feedback mechanisms in a way that leads to a range of conflicting goals [49]. Therefore, increasing our understanding of feedback effects in energy transitions can support researchers and policy-makers in making sense of this complexity, recognizing inertia, and stimulating energy transitions [21].

Feedback effects in energy transition governance

A system can be considered a network of interconnected elements that is arranged for a particular purpose. Previous studies [15,50,51] 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 (e.g. urban heat sector) [52] which are governed via complex structures operating at different levels (international, national, municipal, etc.) [53] with different and often conflicting sets of objectives [21]. Notably, the multi-level perspective framework [50] offers an analytical approach for recognizing interdependencies in socio-technical systems [19,20]. The socio-technical systems framework does not only focus on technological artifacts but also the institutional/governance arrangements, regulations and policies, user practices, and cultural norms that shape the development and use of socio-technical systems over time [50]. At the heart of the framework, energy transitions occur when interconnected elements enable a change in the system configuration [20].

From a transition governance perspective, governance can be defined as the systematic management of societal transitions towards sustainability [20,54]. It refers to structures and processes through which policy-making is coordinated for the desired stability or change in social, economic, and environmental systems [54]. Transition governance is not a static phenomenon but rather involves dynamic processes and networks of actors that span across multiple socio-technical systems [55]. This intertwined relationship implies that policies and energy systems co-evolve: policies influence energy systems, and energy systems influence policies [21].

This influence is not a direct one. Instead, policies and energy systems indirectly interact with the policy subsystem [56]. This subsystem can be conceptualized as a dynamic relationship between actors responsible for policy decisions and interest groups responding to the continuous change in socio-technical systems [56]. Policy subsystems often operate within the broader scope of the socio-technical system(s) and are influenced by the dynamics thereof [21]. This also implies that policy subsystems and socio-technical systems are interconnected through a series of feedback structures [21]. To illustrate this, policy decisions within a subsystem can influence the technological trajectory of socio-technical systems through the development of incentives, regulations, or resource allocation rules which in turn influence the development of specific energy technologies [54]. Conversely, changes in socio-technical systems (e.g. innovations, user preferences) could push policy reforms or changes within policy subsystems [19].

Such feedback mechanisms could lead to unexpected indirect consequences by (re)configuring causal links across energy actors, sectors, and systems [21], resulting in acceleration or inertia during transitions [20]. Therefore, researchers highlight that considering feedback effects in transition governance facilitates the recognition of systemic values and synergies, reduces the risk of stranded assets, sunk costs, and contract breaches, and enables building of long-term strategies that can adapt to fast-paced urban changes [57]. Nevertheless, proper consideration of feedback effects is easier said than done. This is because energy systems are perceived differently by each actor, in conformity with their own expertise, biases, goals, and judgements—in other words, their mental models [19,58]. Actors strive to influence systems to align with their mental models [59]. However, actors are limited in recognizing systemic implications across sectors since they are limited by their own observations, expertise, and biases [19]. Unless feedback mechanisms are considered over a broad range of sectors and long-time horizons [20], policymakers might overlook how other actors would behave as the system changes; thus, policymakers can develop inconsistent policies that could compete with each other or even with overarching sustainability targets [49]. Unfortunately, repercussions from policy-making are often acknowledged too late, for example when inconsistent policies start working against each other, resulting in a heterogeneous set of conflicting goals and outcomes [60].

Mapping out how different feedback mechanisms emerged across Europe, as well as synthesizing how they are perceived and governed differently in diverse contexts, can explain the variance of district heating adoption across the continent, and clarify mechanisms that influenced district heating transitions. Moreover, fostering a feedback understanding with systems models [61] can increase knowledge of how policies and energy systems are interconnected. Exploring the feedback mechanisms responsible for the resilience and transformations of socio-technical systems could support policy-makers in developing governance strategies that recognize and utilize systemic patterns for stimulating transitions [23,24].

Although feedback effects were recognized in transition governance literature [21], it was previously investigated primarily over only a single energy system, set of policies, or sector, which ultimately limits the recognition of broad systemic effects and consequences [61]. In this research, we use district heating transitions as the focal point but also investigate competing and synergistic energy systems over a range of socio-technical themes/factors across Europe. We advance the ongoing debate on feedback in transition governance by generating insights on feedback for achieving net-zero European cities and by explaining how feedback mechanisms could influence policy-making in transitions.

Methodology

We investigated the implications of feedback on governing the substitution of natural gas with district heating systems by modeling the influential systemic causes and consequences for net-zero European cities. As summarized in **Figure 3**, we conducted a systematic literature review where we collected secondary data from academic literature and reports [25]. For the data analysis, we began with open codes to identify the influential socio-technical and governance elements that can influence net-zero district heating systems in cities [62]. We started the analysis from the historical development of district heating systems during the oil crisis in the 1970s and continued until present developments [63]. Subsequently, we used axial codes to categorize influential causal links and feedback mechanisms between policies and energy systems during district heating transitions. By using these codes, we built qualitative SD models [17], specifically Causal Loop Diagrams, to depict potential causes for incremental/accelerated change toward net-zero district heating systems, thereby explaining the impact of feedback in energy transition governance. **Appendix A** includes more information on the data collection and analysis.

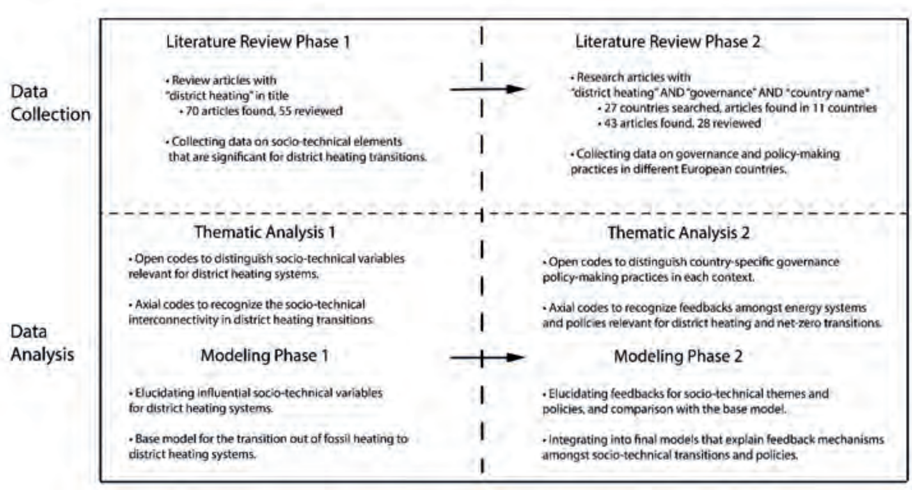


Figure 3 - Methodology chart.

Systematic literature review

For data collection, we conducted two rounds of literature review that included research articles and technical, industry, and policy reports [25]. In the first round, we investigated 55 review papers with the word sequence "district heat*" in their titles. 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, which yielded insights from 11 different European countries[6] [13]. This enabled us to recognize elements that can explain feedback effects between energy systems and policies as well as their consequential influence on net-zero transitions in cities. By mapping out these cooperating and opposing forces, we highlighted and synthesized the implications of feedback on transition governance. Additional articles and reports, identified throughout the review rounds, were included to identify relevant social, economic, technical, and policy dimensions of district heating transitions and net-zero cities.

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 [64]. Such comparative analyses can allow researchers to integrate, recognize, and explain complex mechanisms amongst interconnected policy subsystems and energy systems in accessible diagrams [65]. Therefore, resulting models can explain a range of opposing/cooperating feedback forces that can arise in different European contexts during district heating transitions.

We structured the secondary data by using the four-step coding approach for building qualitative models [62,63,66,67]. First, we utilized open codes inductively to identify influential socio-technical and governance elements for district heating transitions and net-zero cities in different European regions. In the second step, we used axial codes to categorize contrasting claims from different European contexts to identify and explain the cooperating and opposing mechanisms for net-zero district heating systems. 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 [63]. An example of this coding approach is shown in **Figure 4**.

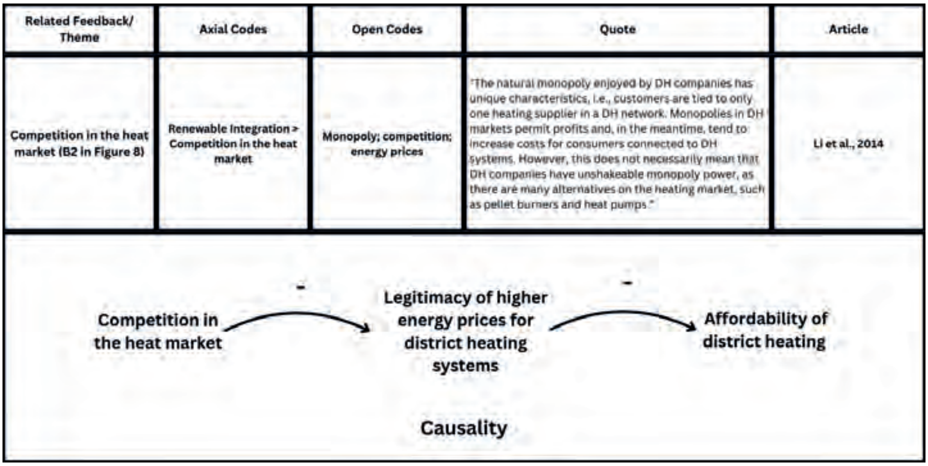
Causal Loop Diagrams

SD models can represent how system elements are interconnected in feedback structures to explain the systemic influences that are responsible for unexpected behaviors [17]. 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 [17].

Closed chains of causalities form feedback loops. The nature of the feedback mechanism, reinforcing or balancing, is denoted as "R" or "B", respectively. **Figure 5** shows an example of reinforcing and balancing feedback [20]. The left part of this figure shows how the increase in population has a positive effect on the birth rate. This increase in birth rate also increases the population, resulting in a reinforcing feedback loop. In such loops, system elements reinforce each other because an initial increase (decrease) in a variable results in a further increase (decrease) of the same variable through a closed chain of causality. Reinforcing loops amplify the initial change in the system and can result in exponential behaviors when left unchecked [17].

The right part of the figure shows how an increase in population also increases the death rate. An increase in the death rate reduces the population, resulting in balancing feedback. Balancing feedback has a stabilizing or limiting effect on system change because it seeks an equilibrium [17]. System elements would continue to change until the goal or limit is reached. In balancing loops, an increase (decrease) in one variable will eventually lead to the decrease (increase) of the same variable through a closed chain of causality. Balancing loops might resist system change if left unchecked [17].

For this research, we used qualitative causal loop diagrams [17], 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 [65].



Related Feedback/ Theme	Axial Codes	Open Codes	Quote	Article
Competition in the heat market (B2 in Figure 8)	Renewable Integration > Competition in the heat market	Monopoly; competition; energy prices	"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."	Li et al., 2014

Figure 4 - Coding example illustrating how models were built. More explanations follow in 3.3.

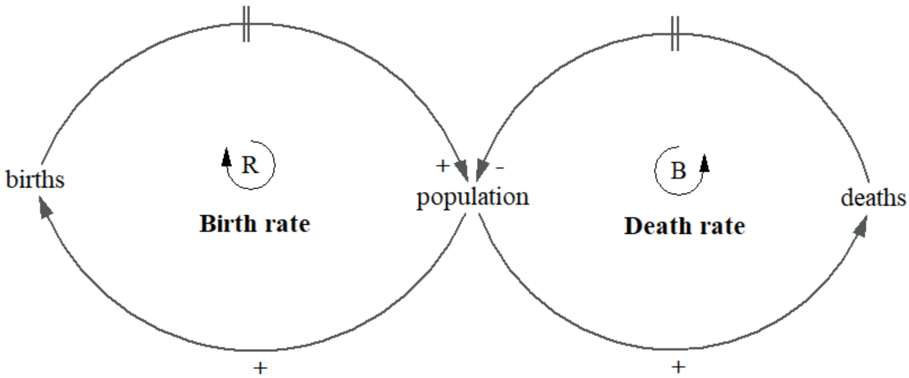


Figure 5 - Example of a causal loop diagram for reinforcing (R) and balancing (B) feedback.

Results

In this section, we first elaborate on the historical development of district heating and natural gas to recognize how these systems emerged path-dependently in different European regions. Then, we distinguish three contemporary themes recurring in the literature under which feedback mechanisms can influence the substitution of natural gas with 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 can accelerate or hinder district heating transitions as a stand-alone mechanism; thereafter, we discuss how interconnected feedback effects may operate together and thus affect the overall system behavior. In doing so, we elaborate on prominent feedback mechanisms that could explain the co-evolution of district heating systems and policies. Finally, we synthesize knowledge from resulting models to highlight the reasons for complexity in transition governance and why socio-technical systems often change in incremental steps rather than through a radical transformation.

Our models show that policies are typically built in policy silos and designed to achieve heterogeneous sets of subgoals [68]. More often than not, different sets of actors are responsible for different subgoals (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 own subsystem but also the whole socio-technical system through interconnected feedback mechanisms. If feedback is overlooked, inconsistencies between policies could lead to sets of conflicting subgoals that can ultimately work against each other and thus net-zero cities [69]. In this research, we argue that there are two prominent reasons for slow-paced change during energy transitions that governance actors should be conscious of. First, policy-makers might overlook feedback in socio-technical systems due to biases or limitations in their expertise [61]. This may lead each actor to focus on achieving different sets of conflicting subgoals during energy transitions [21]. Second, feedback structures might compel the system to achieve more of the prioritized subgoals while overlooking less-prioritized yet still important subgoals for net-zero cities. Unless policy feedback mechanisms are identified and recognized, this may create a snowball effect that favors less sustainable energy systems and thus reduces the pace of energy transitions.

Historical development of heating alternatives in Europe

The oil crisis during the 1970s motivated European governments to consider emerging heating alternatives, as oil prices soared due to the Israel-Palestine conflict [70]. Disruptive influences from the exogenous environment (e.g. economic downturns and international conflicts) create pressure on policymakers to maintain the continuity and quality of societal services while handling such disruptions [21]. The oil crisis provided a window of opportunity for the heating alternatives that were emerging at that time, namely natural gas and district heating systems, to enter energy markets and challenge the existing prevalence of oil-dependent energy generation [20].

Socio-technical factors that prevail in each context can significantly influence how energy systems evolve over time in tandem with the institutions that govern them [14]. Correspondingly, the historical development of heating alternatives diverged into two major pathways in Europe. This was triggered by the (un) availability of fuel sources in each region [71] and by how energy regulations and markets were reformed as a result [72]. The widespread adoption of cogeneration-coupled district heating systems in Scandinavia and Eastern Europe [13,26,73,74] can be attributed to the energy efficiency of CHP plants as well as the available cogeneration fuel in these regions [71]. When oil prices soared in 1973, the primary energy consumption in Scandinavia was highly dependent on oil, at a whopping level of 92% for Denmark and 64% for Sweden [75]. This dependency pushed Danish policymakers into drafting the first-ever Heat Act in Europe in 1979 [76]. This 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 result was an accelerated adoption of district heating systems in Denmark which inspired neighboring countries to develop similar Heat Acts [6,71,76].

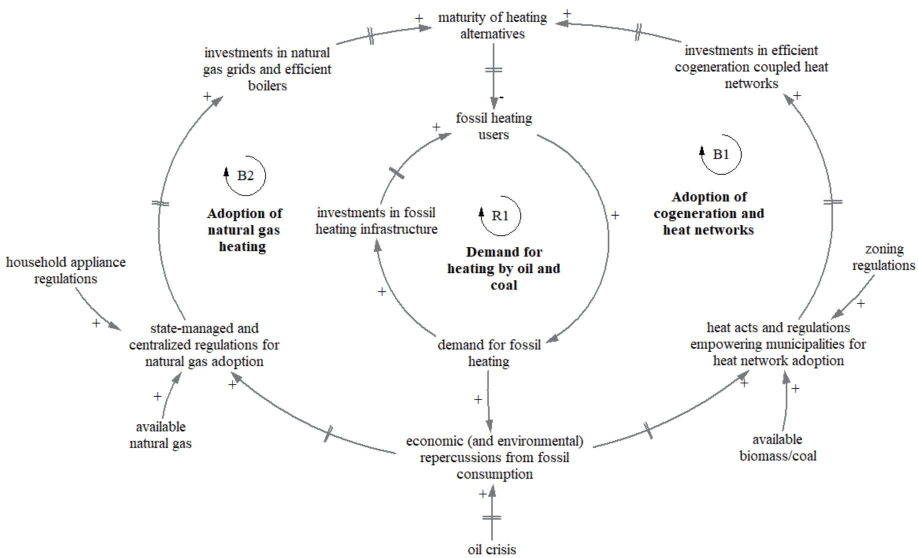


Figure 6 - Feedback mechanisms involved in replacing oil and coal by natural gas and district heating alternatives.

In the case of Eastern Europe, the Soviet Union was not able to satisfy the increasing oil demand even though its fossil production was continuously increasing during this period [77]. Eastern Europe therefore kept buying oil from the Middle East despite increasing prices which accentuated its economic weaknesses. This motivated decision-makers to invest in coal-fired cogeneration and heat networks to reduce the dependency on oil imports [13].

Overall, Heat Acts across Scandinavia and coordinated markets in Eastern Europe [13,71] empowered local governments to invest in decentralized energy production, regulate mandatory connections to heat networks, and thus achieve economic benefits through energy efficiency. In turn, cost-effective cogeneration accelerated the adoption of district heating in these regions [13,74,76]. As shown in **Figure 6.B1**, the oil crisis triggered a transformation of energy systems which allowed the development of district heating systems to balance the negative impact of soaring oil prices [19].

On the other hand, the UK and Netherlands [75,76] found natural gas in their economic zones, in the North Sea and Groningen fields respectively, which enabled a move away from expensive oil (and polluting coal) in energy generation. This also facilitated an in-tandem heat transition on the end-user side towards efficient natural gas-fired boilers. The discovery of natural gas motivated state-managed programs in both countries to actively transform the energy mix and speed up the conversion from oil and coal towards national gas, which entailed regulations for household appliances and the deployment of integrated natural gas grids [71,76]. As a result of these policies [76,78], the number of natural gas users in the UK increased from almost 0% to 46% within two decades whereas the Dutch primary energy consumption by natural gas rose from 3% to 45% in a single decade [75]. These drastic changes triggered investments in research to improve the efficiency of conventional boilers which led to the invention of highly efficient condensing boilers in the Netherlands [79]. This, in turn, further accelerated the adoption and increased the economic benefits of natural gas in these regions to replace oil and coal in heating as shown in **Figure 6.B2**. Countries without fuel availability followed a similar natural gas pathway since it offered a more cost-effective alternative compared to oil as well as a more environmentally friendly alternative compared to coal [76,78]. Condensing boilers are still the most preferred heating choice across Europe [3]. Therefore, the oil crisis triggered different transformations of energy systems in different countries and resulted in the incumbency of natural gas grids and condensing boilers to balance the negative impact of soaring oil prices.

Figure 6 summarizes the feedback mechanisms that facilitated the move away from more expensive and polluting fossils such as oil and coal. **Figure 6.R1** illustrates the demand for oil (or coal) for heating purposes before the oil crisis. The exogenous pressure, i.e. soaring oil prices, triggered policy-makers to reform energy regulations and markets to develop a response. Available responses for policy-makers reflected the prevailing socio-technical factors in each context, in this case, the availability of fuel in each region. This resulted in two different path-dependent trajectories across Europe, towards natural gas or district heating. **Figure 6.B1** and **Figure 6.B2** gradually balanced the prevalence of oil and coal consumption shown in **Figure 6.R1** after the oil crisis. It is important to note that both balancing feedback mechanisms are active across all regions in Europe since both systems exist to some degree in each country. However, the dominance of feedback loops, in other words, whether natural gas or district heating systems are (more) prevalent, depends on the socio-technical factors in each region. Over time, natural gas replaced oil and coal assertively in heat production across Europe due to its cost-effectiveness and relative environmental friendliness, whereas regions, where cogeneration fuel was available, were still able to achieve a high level of adoption for district heating systems.

Energy prices

While section 4.1 focused on feedback mechanisms between natural gas and district heating prices influencing the pace of transitions, **Figure 7** includes feedback effects related to energy prices in the competition between district heating systems and natural gas [61]. Citizens would be more inclined to switch from natural gas to district heating when they perceive district heating as a cost-effective option [61]. In dense urban areas, district heating systems can be a cost-effective alternative for natural gas due to the economies of scale effect, as depicted in loop **Figure 7.R2** [4]. 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 [4][7]. 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 [61], and thus scale up the heat network even further [80]. Moreover, the heat production capacity needs to expand in tandem with the heat network to satisfy the heat demand [19]. This results in an economies of scope effect [81]. 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 [30,82], also portrayed in **Figure 7.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 **Figure 7.R1** and **Figure 7.R2** operating in opposite directions. **Figure 7** 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 natural gas. This reinforces a further increase in cost-effectiveness, number of district heating users, development (or expansion) of heat networks, and investments in compatible heating systems [83]. 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 [4]. This is reflected in Scandinavian examples, where district heating systems do not need incentives or forced zoning regulations anymore [74,76] because they are already considerably cost-effective due to this positive economic feedback.

On the other hand, some authors [61,84,85] argue that certain price mechanisms could impact the pace of replacing natural gas. 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 [85]. As more citizens abandon natural gas, the remaining natural gas users may face higher utility bills because fewer households are responsible for paying the fixed maintenance and operational costs of the natural gas infrastructure [86]. 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 [85]. A similar effect called a utility death spiral was identified for district heating systems [61] and the electricity sector [87]. 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 [88,89]. In recent years, these increasing heat prices resulted in significant subsidization for household energy costs in Europe [90].

High-priced natural gas could create transition barriers for households with energy-poverty challenges. Although higher gas prices would motivate citizens to consider other heating alternatives in the long term [12], unaffordable energy prices could impair households with energy-poverty challenges disproportionately in the short-to-medium term [91] and thus dissuade them from investing in a new system [92], as shown in feedback loop **Figure 8.B1**. Subsequently, increasing energy prices could strengthen the effect of energy poverty by keeping energy-poor households dependent on natural gas heating for longer [92], thereby prolonging the use of natural gas and constraining the switch to alternative heating systems including district heating [61].

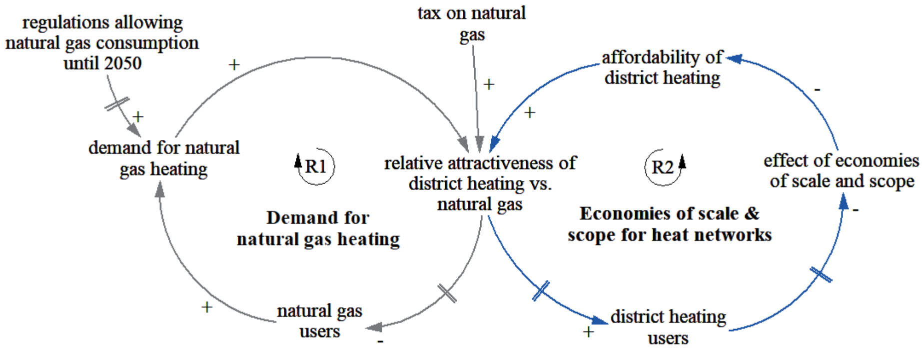


Figure 7 - District heating systems can form positive economic and technological feedback loops, which can scale district heating systems further. This concept model is adapted from [19, 20].

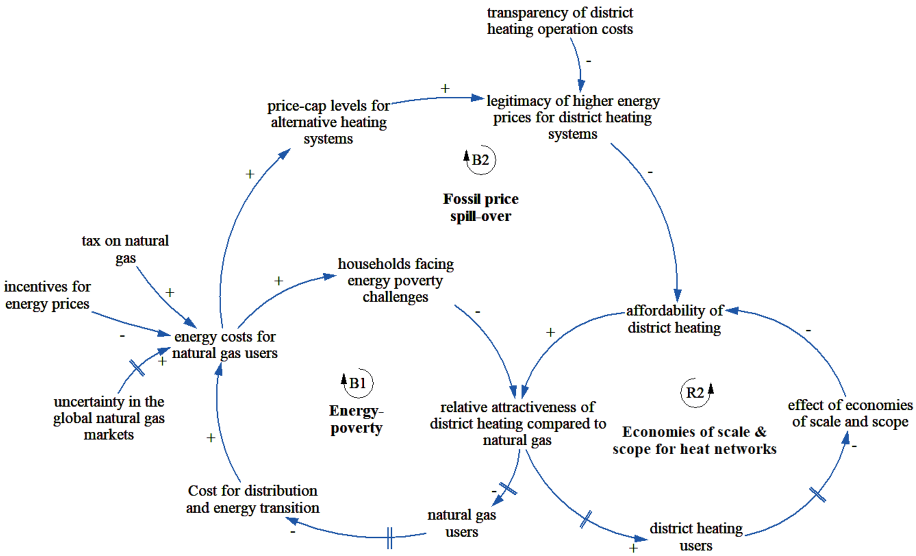


Figure 8 - Price feedback mechanisms that can slow down the replacement of natural gas heating. Feedback mechanism B1 adapted from [19].

Soaring natural gas prices legitimized benchmarking prices for alternative heating sources at higher levels across Europe [93]. 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, give energy companies the incentive to take advantage of cost-transparency challenges in district heating systems [84] to inflate their costs to maximize their profits, as shown in **Figure 8.B2**[8], which implies a spillover effect. Moreover, 27% of the heat networks in Europe today are still coupled to centralized natural gas heating systems [12], which makes the price of some heat networks directly dependent on 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 prices[9].

Overall, **Figure 8** raises an interesting conundrum [20]. 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 [12]. On the other hand, the high prices of natural gas, due to increasing taxes [91], global uncertainties [88], transition costs [89], and utility death spiral [61], could legitimize higher prices for district heating systems through the fossil price spillover mechanism, increase the financial burden on households with energy-poverty challenges, delay the energy transition due to these financial challenges [92], and ultimately work against cost-effective heat networks.

Renewable integration

We now turn to 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 [86]. European cities must, therefore, investigate the potential for all alternative energy sources in their areas, now and in the future, to determine the most practical approach for decarbonizing the urban heat sector [12]. 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 [86]. In doing so, district heating systems can present a significant opportunity to integrate and scale up renewable heat production in cities [86].

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 the users of electricity or natural gas in Europe, district heating users cannot switch heat providers. This is because heat network operators are often vertically integrated energy suppliers [86] who claim the license for district heating sales in that specific region [71]. As a result, heat networks are often natural monopolies [7] which operate under certain price regulations for fair energy prices [86]. 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 [86]. 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 [71], as shown in **Figure 9.B1**. In low- 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 **Figure 9.B2** [86].

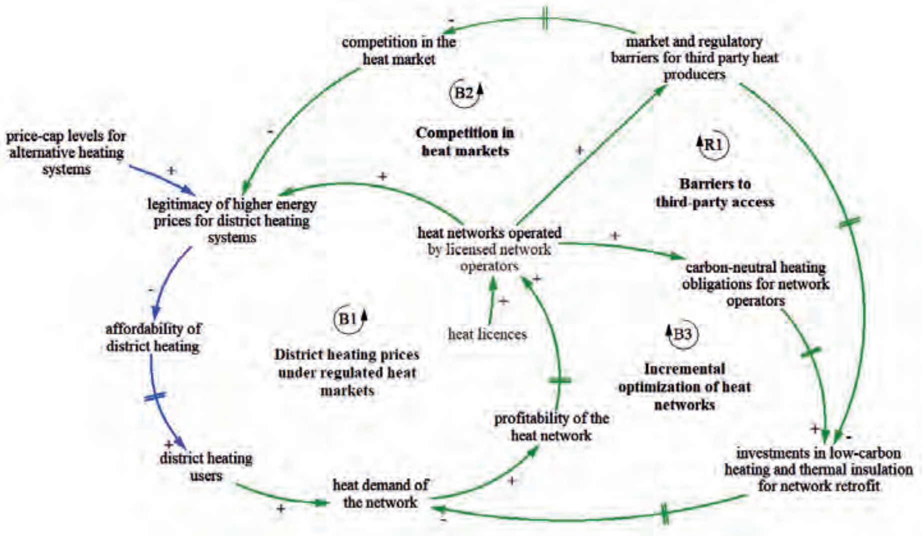


Figure 9 - Renewable integration depends on unbundling and deregulating the heat market, as shown in green.

Low-carbon heating alternatives necessitate insulating the built environment, renovating heating equipment in households, and insulating or replacing distribution pipes in heat networks [39,41]. 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 [32]. On the one hand, insulating the heat 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 [61] 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 **Figure 10**. 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 [84,94] 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 **Figure 9.B3**, network operators still stand to gain if the network retrofit [95] and third-party access are delayed [86]. 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 [71,86]. Restricting third-party access, deregulation, and unbundling could result in incremental optimization by network operators [48] instead of a radical transformation which is needed to scale up the utilization and integration of renewable heating in cities [96].

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 [32]. Achieving these steps, however, depends on breaking out of the incremental optimization trap for heat networks as shown in **Figure 11**.

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 [11]. Existing heat networks are often supplied from one large (or a limited number of) fossil heat source(s) by a single licensed network operator [12,86]. If sustainable heat generation cannot satisfy the

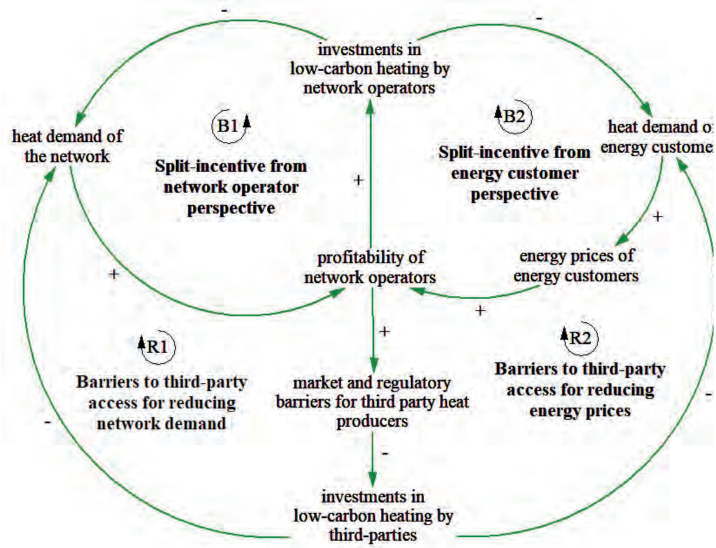


Figure 10 - Split incentives force multiple actors to compete with each other to protect their interests.

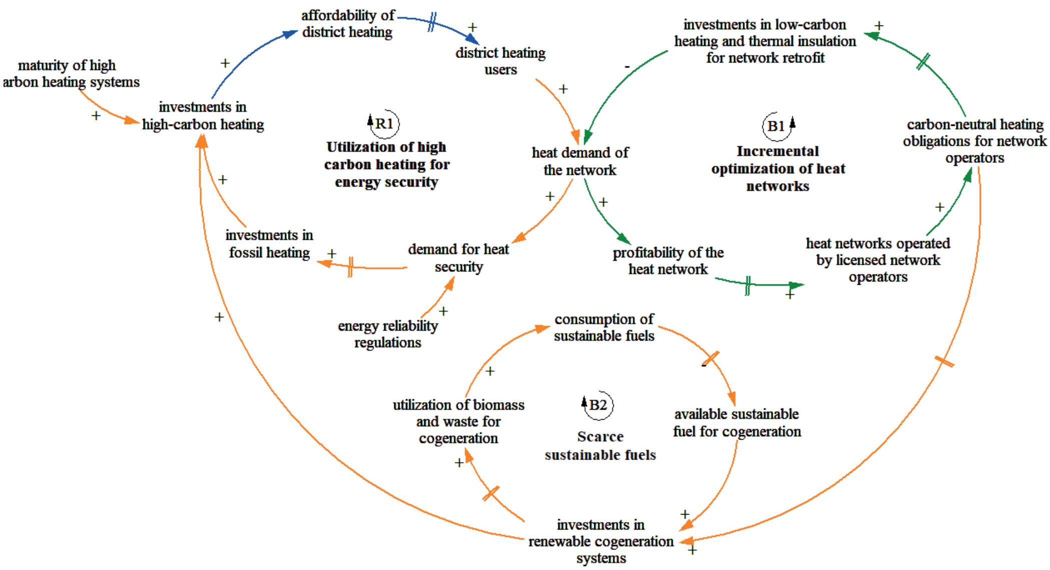


Figure 11 - Mitigation requires breaking the incremental optimization cycle for heat networks shown in orange.

urban heat demand (notably, the share of renewables for heating and cooling in 2020 in the EU was only 23.1% [34]), **Figure 11.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 [8]. Although network operators must follow plans to decarbonize their energy operations, as shown in **Figure 11.B1** [12], challenges to energy security in **Figure 11.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 [95]. 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 [76]. Biomass and waste CHP plants show great potential because they can replace centralized fossil heating systems in heat networks without extensive investments [97] and be coupled with carbon capture systems to mitigate emissions from combustion processes [98]. 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 [12], as shown in **Figure 11.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 [99]. Thus, overinvestments 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 [20]. 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 [61]. This may, in turn, crowd out other mitigation investments [98,100], specifically low-carbon heating systems [101], 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 [99]. 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 [48,102]. Unless an urban strategy 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] [61].

Implications for transition governance

The models discussed above show that the various feedback mechanisms are interconnected. This means that each transition policy influences not just its own policy subsystem, but through feedback loops also a wider range of policy subsystems [21]. These accumulating influences often (trans)form resilient structures across the socio-technical system [69], where energy systems co-evolve to achieve (or fail) net-zero targets alongside the institutions that govern them [48,102]. Our results depict two notable routes through which feedback can influence transition governance. First, feedback effects may reinforce inconsistent subgoals that could compete with each other. Second, inaccurate assumptions or prioritization of competing subgoals could utilize feedback structures to create system lock-ins that could reduce the pace of energy transitions. We illustrate these implications in **Figure 12** in a step-by-step manner to highlight the complexity embedded in transition governance.

Mapping feedback mechanisms allows policy-makers to identify influential system elements, called leverage points [17]. These points interconnect influential causal links and feedback mechanisms in complex systems, as illustrated in **Figure 12a**. They can be used as sensitive signals to recognize how sets of feedback mechanisms could behave in cooperation/opposition to other sets of feedback mechanisms. For example, two significant variables, i.e. network heat demand and legitimacy of higher energy prices, seem to be focal points which interconnect many influential feedback mechanisms in the resulting models. Although policymakers aim to decarbonize district heating systems by enforcing network operators to mitigate their energy operations, the regulatory barriers against third-party access, unbundling, and deregulation of the district heating markets could still delay net-zero heat networks [86]. The monopolistic ownership structure of district heating networks could reinforce barriers to deregulation and unbundling of district heating services [86]. As a result, these overlooked dynamics between interconnected feedback mechanisms 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 [20]. As illustrated, leverage points [17] could build a preliminary foundation on which researchers and policy-makers can start making sense of the complexity of energy transitions.

However, leverage points and feedback mechanisms are perceived differently by each actor by their mental models [68]. In Section 2.2, we stated that actors suffer from cognitive limitations because they all aim to develop systems concerning their own mental models [19]. In practice, overarching sustainability goals, such as "sustainable and net-zero cities", are very intangible, and need to be translated into more concrete, quantifiable, and operational subgoals within different policy fields which operate as silos [68]. 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 [68], as shown in **Figure 12b**. This friction between silos could lead to inconsistent subgoals that ultimately work against each other as actors aim to influence the socio-technical system to achieve different subgoals [49,103]. As a result, policies are developed within a policy silo without considering policies in other silos [104], as shown in **Figure 12c**. 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 might result in policies that support subgoals, interests, and activities within one silo but might be inconsistent with policies in other silos [49].

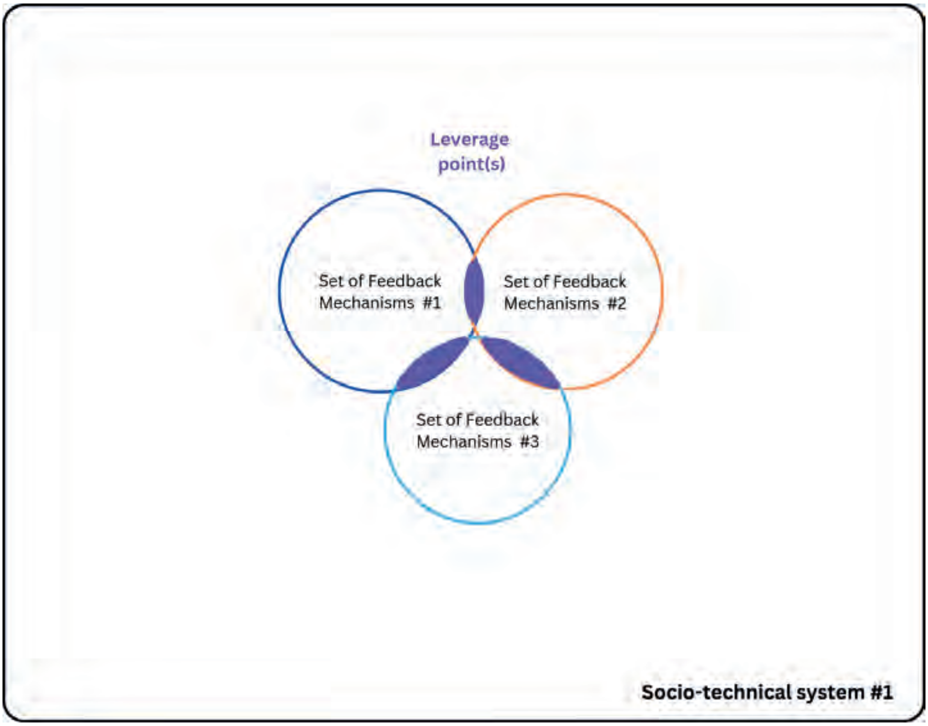


Figure 12a - Leverage points interconnect feedback mechanisms and thus these mechanisms operate in tandem.

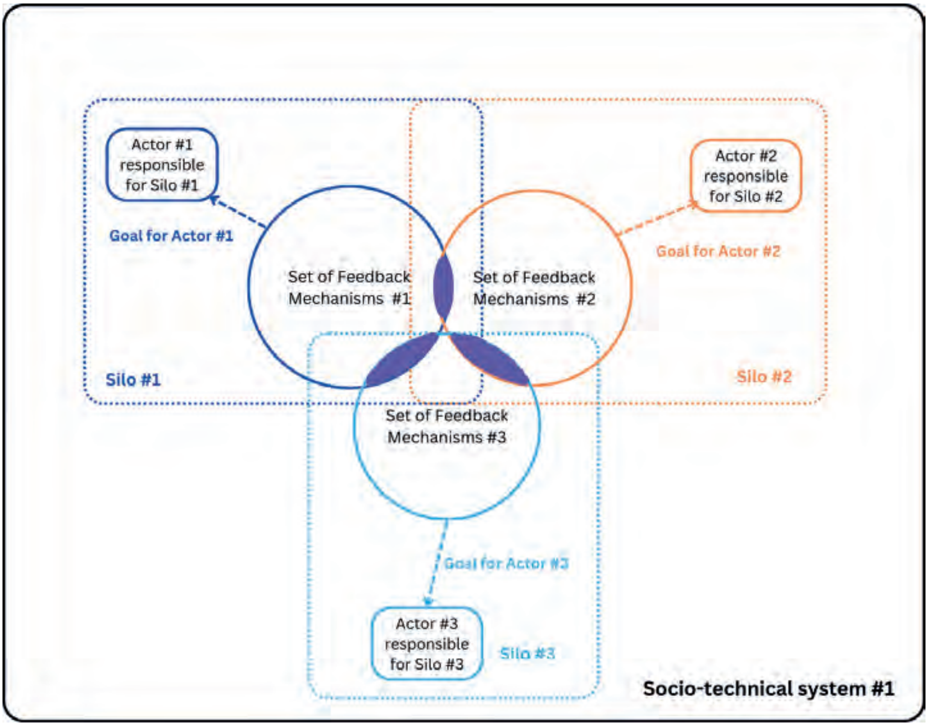


Figure 12b - Actors operationalize overarching goals into disciplinary subgoals in a way that often overlooks other policy silos and actors.

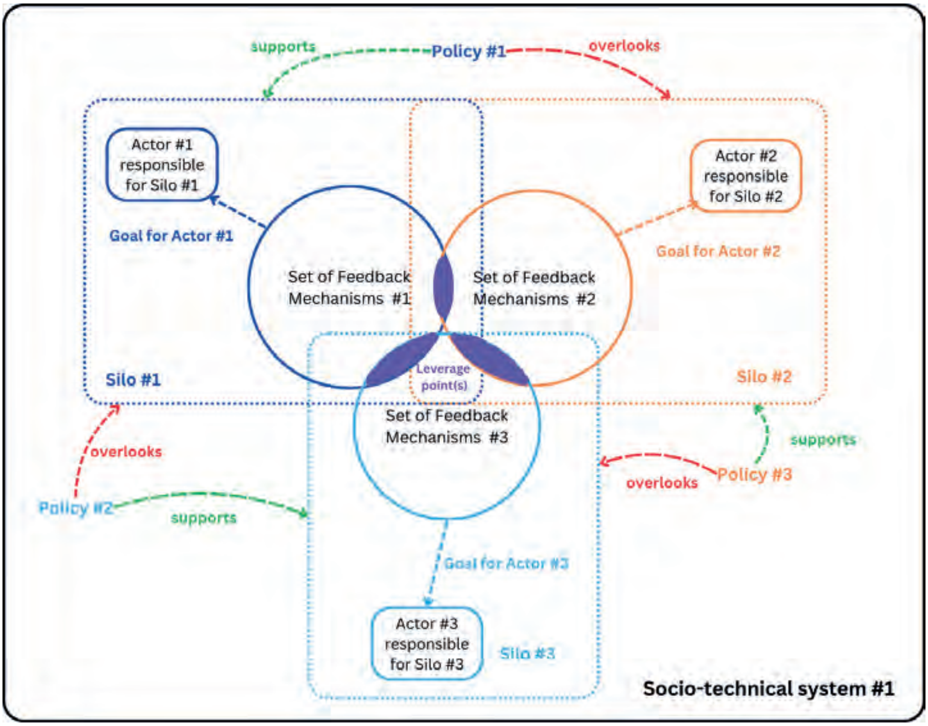


Figure 12c - Policies are often built from the biases of a policy silo to achieve benefits for that specific silo. This can hinder the goals of other silos.

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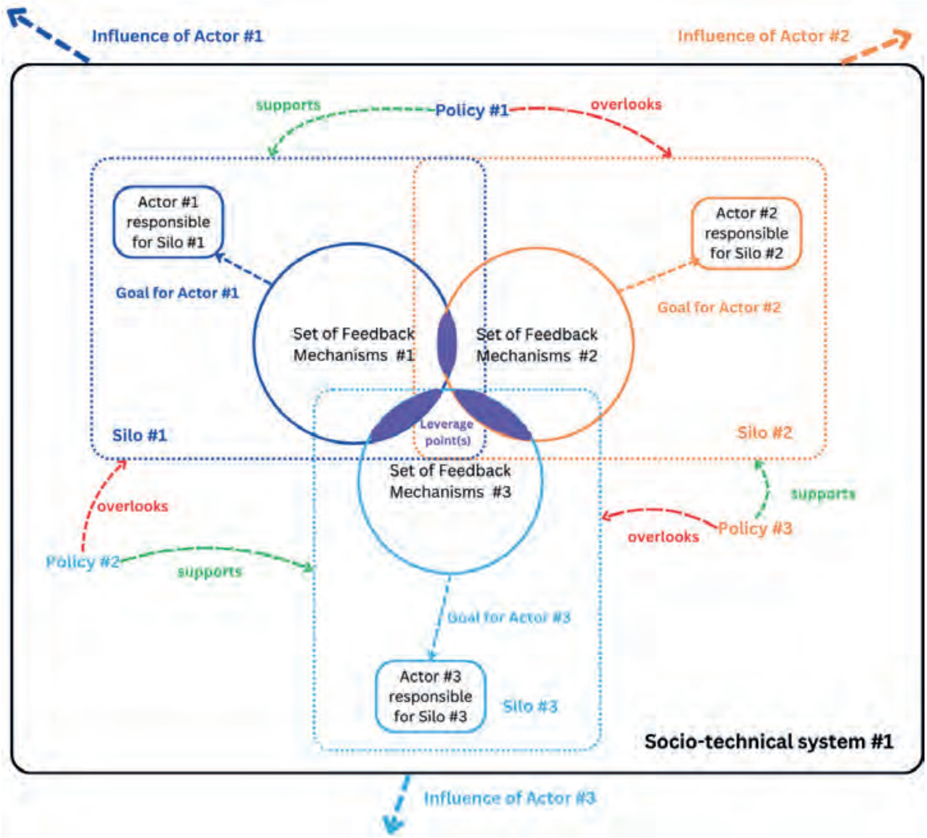

Figure 12d - The (socio-technical) system moves in a certain direction as a result of all accumulated power of all actors involved.

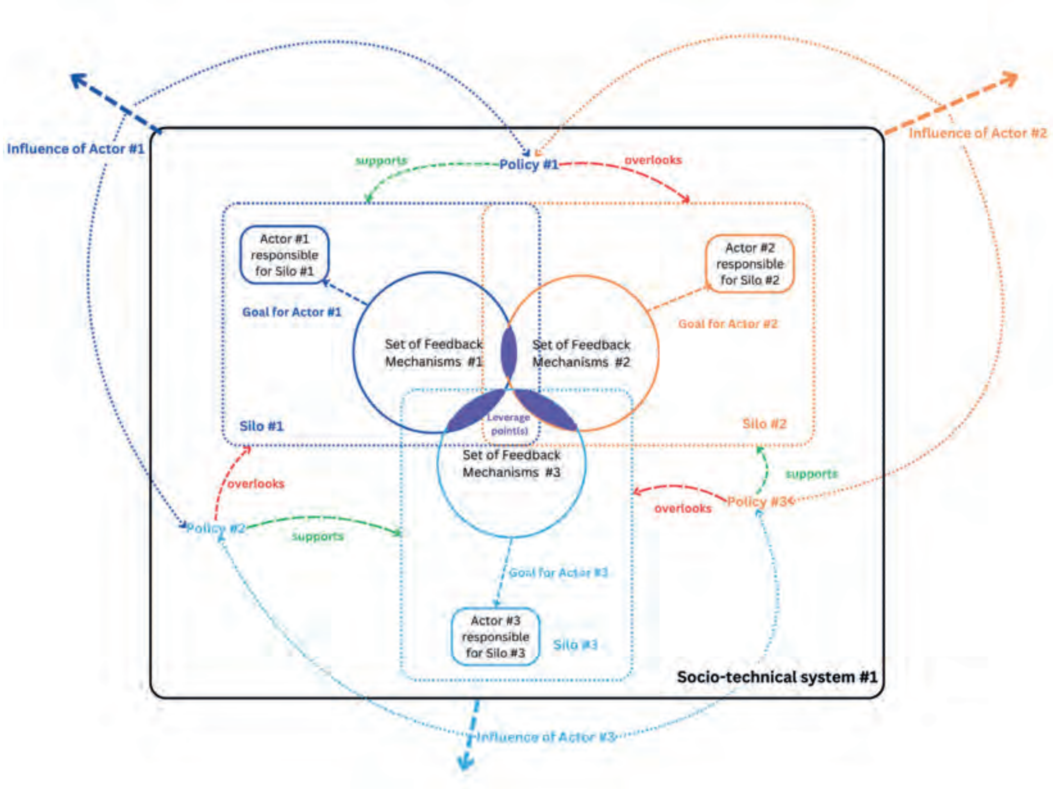

Figure 12e - The movement of the system results in more power being directed towards prioritized subgoals which then reinforces those subgoals even further through feedback mechanisms.

Each policy silo with its own cluster of actors aims to achieve an effect/influence on the socio-technical system in alignment with their own subgoals and interests; thus the resulting behavior of the system is an accumulation of these influences/effects perpetrated by clusters of actors that reside in these silos [20], as shown in **Figure 12d**. For example, the same leverage points, i.e. heat demand of the network and legitimacy of higher energy prices, are interconnected via multiple feedback mechanisms, but most notably in split-incentives and fossil price spillover mechanisms. These feedback mechanisms could lead to conflicts of interest and power struggles such as profitability of energy companies vs. affordability for citizens (fossil price spillover) or sustainability of energy systems vs. affordability of energy services (split-incentive). Although system subgoals are originally intended to contribute to a more sustainable system, feedback mechanisms can pit subgoals and actor interests against each other in feedback structures. This also implies that policies or energy systems cannot always be considered in isolation since they could be interconnected via feedback mechanisms.

To expand on previous examples, the split-incentive issue could be a way for energy companies and policy-makers to legitimize higher energy prices for alternative heating [95] as if they are a circumstantial consequence of energy transition costs [89] and global energy supply challenges [88]. Subsequently, the burden of decarbonizing energy services could be shifted to consumers to maintain the profitability of energy services [88,89]. Thereafter, increasing energy prices, along with the expansion of heat networks, could open up the way for legitimizing continued fossil operations to provide affordable and reliable energy for citizens [8]. This could create legitimacy for more fossil heating for the sake of energy affordability in the short term while delaying renewable integration and thus hindering energy affordability in the long term. As this example shows, the simultaneous occurrence of feedback mechanisms could favor the profitability of district heating services both in the short and long term in the energy market domain while policymakers and actors in other policy fields such as housing seek to achieve affordable and reliable energy services by investing in fossil heating systems.

This indicates a mechanism that feeds the consequential influence/power caused by prioritized subgoals back to the socio-technical system. In other words, feedback mechanisms can keep reinforcing prioritized policy subgoals and actor interests over others at the expense of the pace of energy transitions [21], as shown in **Figure 12e**. To break it down, each silo influences the socio-technical system in favor of its own subgoals and interests [68]. The socio-technical system moves or stands still as a result of the accumulated effects/influences caused by clusters of actors embedded within silos [105], which may reinforce the effects that benefit the most prioritized subgoals. Reinforcing the prioritized subgoals could result in increased influence on policy-making [21], which in turn will prioritize the subgoals even more. This may result in a persistent reinforcing mechanism that favors a specific subgoal while overlooking other subgoals.

At this stage, it is important to note that these interdependent influences/effects across policy silos are very complex, and embedded in the socio-technical system. This implies that policy-makers can seldom achieve optimized decisions, and actors can rarely have total power/control over the socio-technical system. Instead, certain subgoals could be perpetually prioritized over other important subgoals, which could ultimately work against overarching sustainability targets. Some of the ongoing negotiation/lobbying tactics observed across Europe (e.g. lobbying against third-party access [86,106] or against emission reduction strategies [107], threats of discontinuing investments in district heating systems [108], or legitimizing the prolonged use of fossils to guarantee energy security and/or affordability [109]) illustrate the influence on policy-making discussed in this paper. On the one hand, these actions could work in favor of certain subgoals such as promoting the profitability of network operators or energy security, which are essential for urban transitions without disrupting energy services [61]. On the other hand, placing excessive emphasis on these subgoals while neglecting others could activate mechanisms that might lead to lock-in, or at least prolonged consumption, of fossil fuel-based energy systems [61]. Unless feedback in transitions is acknowledged by policy-makers, it could work against net-zero targets due to wrong assumptions and prioritizations of subgoals [61].

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, time frame, path-dependencies, etc.) [20]. A systems-level understanding can support researchers in identifying the complex and persistent feedback structures that result in path dependencies for energy systems in each context [21]. Insights into how energy systems react to changes in governance and vice-versa can shape our understanding of co-evolution [21]. Therefore, understanding feedback effects and their implications can provide useful insights for policy-makers to understand the impact of (unknown) interdependencies and to develop more integrated policies for stimulating energy transitions [20,57,61]. Although recent literature acknowledges (in)consistencies in policies [21,48,110,111], policy feedback mechanisms [21,112,113], and socio-technical interdependencies [18,114,115], 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 on a purely theoretical level. This implies that the implications of feedback 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 [19] 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 [12]. We started our analysis by considering the long-term effects of path dependencies [20] to understand their influence on contemporary heat transitions in European cities. Although district heating and natural gas systems are at the focal point of this research, we still included other complementary/competing systems in the analysis [19] (e.g. renewable heat production, insulation) to recognize indirect effects from potential feedback mechanisms. Utilizing a systems lens can enable researchers and policy-makers to cut through the complexity that different governance levels and/or policy fields bring to energy transition challenges. By developing systems models, we showed how diverse sets of feedback effects operate in tandem, sometimes in similar directions and sometimes in opposite directions. As the system changes, the mechanisms of feedback effects also change. These dynamics result in much more complex system behavior than has been discussed in the literature [20,61,110], as illustrated in **Figure 12**. This indicates that most if not all policies are indirectly interconnected through a range of feedback mechanisms.

Due to the complex nature of energy transitions, policymakers might underestimate the impact of feedback effects in transition governance. This follows from the narrow focus on policy subsystem(s) or silos, which is necessary for dividing sustainability targets into operational subgoals. However, this process often neglects efforts in other silos and policy subsystems. Inaccurate assumptions about feedback [20] could lead policymakers to develop inconsistent policies that aim to achieve a heterogeneous set of conflicting subgoals. Overlooking complex higher-order effects, triggered by policies and actions from other subsystems, could lead to unintended systemic consequences [61]. For example, it is understandable that energy companies aim to maximize the profitability of their services [86]. This is typically caused by high levels of investments and long recouping times in infrastructure projects [116,117]. 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 [71,86]. Overlooking feedbacks could blindside policy-makers and actors [118] by making them consider and act on short-term gains by adopting an isolated policy subsystem perspective which might eventually constrain systemic long-term benefits for all actors including themselves.

Furthermore, neglecting feedback effects in transition governance could shroud the (potential) dynamic changes in system behavior triggered by feedback mechanisms [20]. To illustrate this point, the reinforcing feedback between the profitability of district heating services, affordability of energy prices, and economies of scale and scope is a great example where focusing solely on a disciplinary subgoal might hinder (or support) the energy transition, thereby influencing the same goal again in the same direction. If the district heating systems keep relying on a high-temperature design for longer periods, urban heat consumption and energy prices could stay relatively higher due to the pressure on fossil prices by increasing taxes and global uncertainties. This would eventually delay investments in alternative heating technologies or insulation, and thus further legitimize the use of fossils to keep energy prices relatively lower. Although this could be successful in the short-to-medium term, long-term prices would still rise as fossils are gradually taxed more to achieve carbon-neutral heating. When competing subgoals exist, in this case, affordable energy prices vs. urban mitigation, one subgoal could be prioritized over the other to benefit society in the short-to-medium term. However, as the example shows, prioritizing one subgoal over others also constrains the system as a result of interconnected feedback mechanisms [21]. Although investing in further fossil capacity could keep the short-term energy prices lower, it also decreases the potential price reduction in the long term via renewable integration.

Aligning policies calls for understanding the nature of policy subsystems and reconciling silos through systems understanding and methods [104,119]. This could support researchers and policy-makers in identifying potential blind spots and points of conflict amongst different subsystems [120,121]. This allows recognizing the necessary compromise between disciplinary targets and policy subgoals, thereby building a better foundation for more integrated policies [122]. Overall, modeling feedback effects to govern transitions could provide a useful tool to proof policy instruments and challenge "simple" fixes by policy-makers to solve energy transition challenges [103], such as "implement hydrogen technology", "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. 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 throughout 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.

Limitations and Future Research

Although recognizing feedback in energy transition with systems models could support policy-makers in building integrated policies and aligning subgoals [20,68], all models ultimately represent a static and aggregated snapshot of the system [123]. First, there is no single socio-technical system, goal, or policy, as shown in **Figure 12**. Rather, there is an array of these components which increases the complexity of analysis [124]. 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 [20]. Choosing different boundary assumptions is bound to bring a range of different research results. Finally, using only a systems lens to govern transitions would only work under the assumption that all actors are in alignment to achieve overarching sustainability target(s) [120]. Our results indicate that no single model can fully encapsulate the complexity and dynamicity of socio-technical transitions.

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 mechanisms will support policy-makers and researchers in reconciling silos and recognizing interconnectedness amongst policy subsystems while making decisions.

Conclusion

We investigated feedback effects involved in the substitution of natural gas-fed district heating systems towards net-zero European cities to highlight the complexity of transition governance. We conclude that the co-evolution of policies and energy systems might activate mechanisms that could stagnate transition efforts unless feedbacks are recognized and subsequently managed throughout governance processes. Revealing these 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 governance seldom consists of "simple" fixes as often claimed by popular policy-makers or influential actors because each decision impacts the whole system. Utilizing systems models could support governance efforts by highlighting and increasing our understanding of the interconnected mechanisms in energy systems, thereby enabling more open discussions in governance processes to recognize, adapt, and manage the unexpected dynamicity during transitions.

Footnotes

1. Heat pumps are considered another key technology for enabling the energy transition and carbon neutrality for the EU. While they are economically viable on a macroeconomic scale, the high upfront investment costs involved hinder their deployment at a small scale in many EU countries. The advantage of heat pumps is that they are viable individual solutions and can be deployed as soon as the thermal efficiency of the building allows [1,125].
2. 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.
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   https://www.flaticon.com/free-icon/water-pipe_4524481
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3. **Baseload heating systems** [43] can produce enough heat for baseload heat demand. Most heat networks utilize the unvarying power-generation capability of combustion technologies. Baseload heat can be also produced by combining multiple dispatchable intermittent systems.

   Dispatchable heating systems need to cooperate with other energy systems to provide enough heat for baseload heat demand or they can be dispatched during peak loads and imbalances. Dispatchable systems generate varyingly depending on conditions such as peak loads and imbalances, availability of intermittent heat sources (e.g. solar, wind coupled heat pumps, residual heat), and economic conditions for heat generation type (e.g. utilization of heat pumps when electricity prices are low). In newer-generation heat networks, small-scale renewable sources need to be dispatched when conditions are favorable, and work together to provide the baseload demand. Except for Iceland [13], there are no countries that can create almost all of its baseload heat demand with renewables. In Iceland's case, available geothermal energy coupled with district heating systems provide most of the island's power and heat generation.

4. Cogeneration systems combine electricity and heat production systems in a single plant. CHP plants are traditional combustion plants which can recycle the cooled-down water for heating purposes via heat networks after producing electricity. A conventional fossil power plant operates at an energy conversion efficiency ratio between 35% and 40% [126]. The remainder of the produced energy is lost to the environment. In contrast, cogeneration (power and heating) and trigeneration (power, heating, cooling) solutions can increase this ratio up to 65-90% [127,128]. This is because the energy-carrying water is further cooled down after each energy production cycle (power, heating, cooling), increasing the overall efficiency of the combustion processes in CHP plants. As a result, cogeneration (and trigeneration) coupled heat networks can increase energy efficiency by linking the heat and electricity production at the city level [129], and thus significantly reduce the dependency on fossils and fuel imports [7].
5. The countries were identified by the previous European Union research project WEDISTRICT on district heating systems [13]. Notably, this project identified the regional opportunities and challenges for each European country for district heating transitions along with generic policy suggestions for district heating transitions across the continent.
6. 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 [4]. 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.
7. 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 [84].

8. Spillover is a broad concept that refers to interconnections between emission-reduction policies, industry, infrastructure, market organization, and technology implementations [20]. 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 **Figure 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.
9. 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 [48].

Table 4 - Heat generation type by technology [10, 27, (Lund et al., 2014; Mazhar et al., 2018; Kayegh et al., 2017; 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.

10. Split-incentive issues are often discussed for property owners and tenants facing thermal insulation challenges in the built environment [130]. Property owners need to invest in thermal insulation while tenants benefit from these investments. **Figure 11** implies that a similar effect might be relevant for net-zero networks as well.
11. 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 [131].
12. Norway and Finland are exceptions because of their continued high dependency on oil over the years and low urban densities, which, in turn, favored electrification and heat pumps as the de facto heating choice [71,76].
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 [108].
14. Our models illustrate multiple examples of such contested elements: the urban heat demand is pushed in different directions due to the split-incentive issue in net-zero networks, investments in high-carbon heating might be prolonged due to energy security if renewable sources cannot match the urban heat demand or fossil price spillover can influence prices for alternative heating.

Appendices

Appendix A - Data collection methods

More information on the data collection and analysis methods can be found in the accompanying Mendeley data folder, accessible via the following link: https://data.mendeley.com/datasets/z4mmgzpmvv/1

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Figure 12c- Policies are often built from the biases of a policy silo to achieve benefits for that specific silo. This can hinder the goals of other silos.

Chapter 6

Conclusion

Summary of the research

The objective of this thesis was to advance the understanding of feedback effects in energy transitions by exploring their systemic implications and promoting interdisciplinary communication via SD models. This research utilized qualitative SD models to recognize and address the complexity caused by interdependencies in socio-technical systems to help scholars and policymakers to develop policies for net-zero energy systems which can cope with feedback effects. Each chapter explored various facets of interdependencies in different energy transitions to increase our understanding of the complexity caused by feedback effects for energy transitions and transition policies.

The second chapter [1] investigated 25 different energy infrastructures within the electricity, heat, and transportation sectors relevant to Dutch cities toward a net-zero future. Synthesizing the knowledge from socio-technical systems and multi-modal relationship frameworks [2–4] provided a rich setting to examine and discuss interrelationships among energy infrastructures for conceptualizing socio-technical interdependencies. This chapter demonstrated that energy infrastructures influence each other, forming a myriad of socio-technical interdependencies [5]. These interdependencies ultimately influence how energy infrastructures develop, operate, and evolve [6]. As more or less resilient causal structures are formed between energy infrastructures, socio-technical interdependencies significantly accelerate or stagnate energy transitions [1]. This chapter highlighted that each city can be observed as system of systems, or a nexus, where socio-technical interdependencies co-evolve as a result of each city's historical, geospatial, technical, socio-political, and temporal context. Although feedback effects were not specifically mentioned in this chapter [1], **Table 2** shows that energy infrastructures are interrelated in many ways, and these interrelations can lead to feedback mechanisms. As such, this chapter acted as a conceptual foundation for the study of feedback effects in socio-technical systems in later chapters.

The third chapter [7] introduced qualitative SD models as a tool to explore and analyze feedback effects in energy transitions. This chapter analyzed natural gas, coal, solar, and wind technologies in the electricity sector to study how natural gas can be utilized as a transition fuel. The results from this chapter highlighted that indirect effects in energy systems could influence the success and pace of energy transitions. The term 'indirect effects' refers to global, delayed, long-term, and non-linear effects, which are typically considered as higher-order consequences of feedback effects [7]. This chapter illustrated a number of feedback effects, or bidirectional interdependencies, that are responsible for unintended consequences in the electricity sector [7]. To illustrate, this research highlighted a fossil spill-over feedback between coal and natural gas because their relationship is not solely dependent on price mechanics as many authors claimed [7]. If overlooked, such feedback effects could work against transition policies and efforts (e.g. competition between US fossil markets increased European coal consumption [8]). This chapter concluded that addressing unintended consequences during energy transitions necessitates recognizing these indirect, and often unwanted, impacts of transition decisions and policies by considering a range of energy technologies over a long time horizon [7].

The fourth chapter [9] investigated the switch from natural gas heating to a district heating system in a zone in the center of Rotterdam. This case study started from the conceptualizations of the second chapter that urban (heat) transitions depend on each city's historical, geospatial, technical, socio-political, and temporal context. This chapter demonstrated that feedback effects in energy transitions are influential for and influenced by the city's context in which energy systems are embedded [10,11]; moreover, path-dependencies in each local context drive future pathways for energy transitions [12]. Overall, the initial design of transition policies can influence potential pathways for the future and often brings about a "path of least resistance" which is typically discussed as a no-regret solution. However, the (deliberate) choice to develop these solutions could lead to a slow-paced incremental development during energy transitions through feedback effects [9]. As the examples in this chapter show, advancing understanding of these feedback effects informs scholars and policymakers and aid them in addressing potential path dependencies in local contexts to stimulate energy transitions [9,13].

The fifth chapter [14] investigated district heating transitions across the European continent by analyzing the co-evolution(s) in district heating systems and natural gas since the 1973 oil crisis and developing a feedback understanding of the contemporary developments and challenges for the switch from natural gas heating to district heating systems. This chapter demonstrated how feedback effects in energy systems and transition policies operate in essence and how unexpected policy consequences can emerge from these feedback structures [15]. Overall, the development of policies in isolated silos could result in unintended effects for other policy domains [16], thereby influencing the feasibility of certain pathways for the development of future energy systems [17]. This effect might be further reinforced as feasible pathway(s) for energy systems ultimately shape and constrain future transition decisions and policies, forming a feedback mechanism *between* energy systems and transition policies. This implies that "simple policy fixes" seem to contribute to solutions to short-term problems of the energy transition but might ultimately perpetuate the overall energy transition challenges that they are trying to solve [18]. Without a more systemic understanding, policymakers might overlook how other actors and policy-makers in other silos react to what seems to be a "simple fix".

This thesis set out to answer the following main research question: what feedback effects affect energy transitions and their governance? To answer the main research question, each article explored and advanced the debate on various feedback effects that help or hinder energy transitions in different settings, such as economies of scale and scope [7,9], lock-in [1,7,9], energy rebound [7], crowd-out [1,7,9], price spill-over (fifth chapter), carbon leakage [7], split-incentive (fifth chapter), and so on. The research findings indicate that policymakers should be aware and capable of addressing any unintended consequences that may arise from their decisions. This suggests that policy design should be an ongoing process in which communities, experts, policymakers, and researchers continuously assess and (re)adjust policies at significant turning points. With aforementioned articles in the previous chapters, this thesis contributes to the ongoing discourse on transitions in energy systems [2,19–21] and provides insights on feedback effects to advance transition research [10,15–17,22]. The development and use of qualitative SD models can aid researchers and policymakers in identifying, understanding, and addressing the feedback effects during energy transitions [7]. The interconnectivity between transition policies and energy systems [12,23] means that transition governance needs to be designed to account for such dynamics. This also means that transition governance need to be adaptable to change for dealing with unexpected issues that arise because of feedback effects throughout different phases of the energy transition [7,9]. Thus, the real challenge in transition governance is that institutions need to be designed with the capability to co-evolve and be able to take into account the consequences of previous transition policies and developments in energy systems [15].

Contribution to academic literature

It becomes evident that energy transitions call for a systemic and interdisciplinary approach that acknowledges feedback effects and studies underlying mechanisms and potential unintended consequences [24]. Although the literature on socio-technical systems and transition governance acknowledges feedback effects as a crucial concept for policy-making in energy transitions [15], Köhler et al. [25] emphasize that this strand of research needs to develop further from conceptual discussions towards forward-facing policy-making methods capable of understanding and addressing complex new as well as persistent problems in ongoing transition challenges.

This thesis drew heavily on three bodies of literature: system dynamics, socio-technical systems, and transition governance literature. This thesis contributes to the ongoing academic debate by proposing SD modeling as an interdisciplinary framework, communication tool, and participative co-creation approach which can aid scholars, policymakers, and energy experts in exploring, recognizing, and addressing feedback effects in energy transitions. The use of qualitative SD models promotes interdisciplinary communication and collaboration between scholars, policymakers, and energy experts by building a shared understanding of how pathway(s) for future energy systems could be influenced by interdependencies and feedback effects in energy systems. On the whole, synthesizing SD modeling approaches with transition research literature and frameworks, as this thesis did, could benefit scholars and policymakers in making sense of complex behaviors during energy transitions. The following subsections discuss each body of literature separately.

System dynamics

Synthesizing two bodies of transition research strands, namely socio-technical systems and transition governance, to build system dynamics models is not a straightforward endeavor. An energy system is an embedded part of another higher-order system (i.e. an electricity system as part of an energy system, which is part of an infrastructure system, that is part of an urban services system, and so on) [26]. Thus, it is hard to generate holistic knowledge because scholars and policymakers tend to prioritize and conceptualize "sustainable energy" according to their responsibility and/or disciplines [4], which then feeds into scholarly as well as policy silos [7]. Unless explicitly trained, scholars and policymakers tend to focus on narrow problem boundaries which are governed by 'traditional' sectoral governance structures, thereby increasing the chance of missing cross-sectoral, more indirect yet relevant feedback mechanisms [27].

This study was able to explore the complexity in energy transitions due to its broad analysis scope ensured by the strengths of qualitative SD modelling and a vast range of data sources [28]. Using different primary and secondary data sources in different projects (integrative reviews, interviews, group model building) allowed this thesis to develop a broad scope to investigate these complex behaviors, caused by feedback effects, with SD models [7]. Qualitative SD models can embed the interdisciplinary knowledge and span across a broad research boundary for tackling complex issues. Especially, each article in this thesis incorporated integrative reviews which allows researchers to draw from and complement disciplinary studies [29]. This type of review embed opposing arguments to develop a systems understanding, and thus generate novel insights that surpass the pieces of "interdependent" knowledge accumulated from different disciplines [7]. By synthesizing transition theories and frameworks with SD models with a vast range of primary and secondary data, this thesis was able to explore and explain the complex system behavior (e.g. lock-in, crowd-out) responsible for the co-evolution of energy systems [19,23].

To illustrate this with an example, the "no regret transition" in Rotterdam [9] is an example of co-evolution [23,30] among energy systems, transition policies, and cities [10,15] where locally available high-carbon heating technologies could potentially crowd out the sustainable heating technologies necessary for a net-zero district heating system in the near future unless additional policy measures are taken [9]. As the example shows, the models developed in this thesis conceptualized frequently debated issues in energy transitions which are related to feedback effects (e.g. fossil spill-over due to crowd-out [7]) and explored the mechanisms responsible for the complexity during energy transitions [7,9].

Socio-technical systems

To develop forward-facing methods for transition management [25], scholars call for conceptualizing and envisioning the embedded complexity and interconnected nature of energy systems [1,7]. This is because interdependencies and feedback effects in energy transitions can change how they behave under different circumstances (e.g. tipping points [25]), thereby influencing the pace and impact of energy transitions [7]. These systemic consequences from interdependencies and feedback effects can be recognized when the scope of analysis includes multiple socio-technical 'levels and dimensions' [2,31] and encompasses several disciplines [32]. Qualitative SD modeling can provide the methodological framework to explore and analyze complexity in energy transitions, and thus aid scholars and policymakers in thinking through potential consequences from higher-order consequences resulting from feedback effects before they materialize.

The findings from this thesis corroborate previous research on socio-technical systems, suggesting that energy transitions could be accelerated or hindered as a result of interdependent mechanisms in socio-technical systems [5,6,33] because feedback effects can occur between seemingly isolated or unrelated socio-technical levels and dimensions [1]. To illustrate, the fourth chapter [9] highlighted that achieving a net-zero district heating system is simultaneously dependent on many factors across the socio-technical system, including but not limited to, insulating the urban area, stimulating low-carbon heating technologies, limiting investments in high-carbon technologies and carbon capture and storage systems, scaling the heat network in accordance with the existent low-carbon heating capacity, and ensuring the necessary societal support to activate economies of scale for the heat network [9]. Alas, each of the abovementioned sustainability goals are governed in different institutional settings. Consequently, managing energy transitions requires not just foreseeing the impact of decisions on immediate policy domains, but it is also essential to analyze and comprehend the overlapping interrelationships between policies for socio-technical system(s) under investigation. This implies that cross-sectoral collaboration and cross-disciplinary policy-making are essential ingredients for adaptive policy-making which can ultimately address unintended consequences that can arise during energy transitions [34,35].

Transition governance

This thesis highlighted that energy transitions can be met with resistance [8] unless policies and regulations create an environment that stimulates the intended change in energy systems [36]. Energy technologies, actors, and policymakers are active in a range of policy subsystems that aim to operationalize and achieve a set of heterogeneous sub-goals [15,16]. This also implies that simple policy fixes, often advertised by policymakers towards a specific goal, can rarely achieve what they set out to do because they overlook (or ignore) higher-order consequences of feedback effects [15]. The energy transition is not a simple technological change or innovation which need implementing; instead it is a societal change which encompasses how energy is produced and consumed as well as how energy systems are managed and governed.

Policy integration is an umbrella term that refer to the governance of cross-cutting issues in policy making which transcend the boundary of established policy fields and domains [37]. The cross-cutting issues do not always correspond to the institutional responsibilities of individual departments; thus, research calls have been made to integrate “fragmented decision-making” for interrelated policy domains [37]. A variety of related (or synonymous) terms were used in the academic literature to discuss this issue [37], including but not limited to, policy coherence, cross-cutting policy making, policy consistency, policy coordination, multi-level governance, etc. [16,37–40]. Policy integration or integrated policy-making refers to both horizontal (e.g. different departments in a municipality) as well as vertical integration (e.g. multi-level governance [39,41]), or combinations of both [37]. The concept of policy integration implies that interdependent policies could activate systemic mechanisms that work for or against each other [15], thereby influencing the success and pace of energy transitions [7,9]. If there is a lack of collaboration between policymakers, overlooked feedback mechanisms could work for or against net-zero energy systems in the long run in unexpected ways [36]. Developing models of feedback effects in energy transitions allowed this thesis to recognize and explore future path-dependencies and systemic consequences that could help scholars and policymakers develop future policies.

Many scholars suggest co-creation approaches [11,42,43] to increase participation in decision-making and communication across disciplines as an instrument of integrated policy-making [37]. Notably, the fourth chapter used group model building as co-creation approach, where stakeholders jointly developed SD models of the complexity in an ongoing transition in Rotterdam [9]. Participative modeling approaches allow for the exploration of different potential energy pathways and explore conditions for those pathways with stakeholders who are experts in and responsible for different (policy) domains. Participative modeling workshops offer a co-creation environment [44] where scholars can identify and recognize "disciplinary" information which in turn can be used to conduct interdisciplinary or systems analysis [1,9]. By using participative modeling approaches, integrative reviews, and qualitative SD models, this research advanced the debate on integrated policy-making in energy transitions by conceptualizing the complexity of feedback mechanisms across different policy domains and energy sectors.

Interpretation and synthesis of findings

Organizational and functional fragmentation is an endemic characteristic of public policy [35]. This fragmentation is necessary to manage tasks and draw lines of responsibility for experts who have in-depth knowledge for achieving a specific purpose [45]. As the fourth chapter demonstrated [9], although urban insulation and heating technologies significantly influence each other, these decisions need to be led and managed by different parties due to the required technical expertise, area of influence, and policy domains. This fragmentation allows efficient resource management and streamlined decision-making to achieve complex societal goals which almost always consist of multiple policy sub-goals [45]. Policy silos can lead to failures [40] when experts have strong within-unit coordination but lack cross-unit coordination [46,47]. In other words, transition policies can work against net-zero energy systems in the long term due to the fragmented policy-making practices in policy silos if and when there is a lack of communication and coordination beyond immediate domains of responsibility [35]. The resulting models in this thesis corroborate this fact [7,9] since fragmented and siloed policy-making was identified as one of the main culprits for resistance against change via feedback mechanisms [8].

Policy silos are, in fact, a natural social organization mechanism to break down complex policy environments into manageable and operational scopes [45] for complex undertakings such as energy transitions [35]. This follows from the fact that silos allow for the diversification of disciplinary expertise and streamlined resource management which are essential for completing multi-faceted projects [34]. For example, an engineer or decision-maker who is an expert in low-carbon heating might not know or understand the ongoing insulation regulations and processes, or vice versa. Breaking down silos in one policy domain could create new silos in other domains. Therefore, it is safe to say that integrated policy-making does not mean the absence of policy silos, but this concept rather discusses what cross-cutting collaboration should look like if and when interdependencies in policy-making are taken into consideration.

Recent studies have been focusing more on how silos could be reconciled rather than destroyed [34,35,37,40]. The more precise art and form of how to develop and design for the possibility of reconciliation among policy fields emerges as a new form of governance focus. However, our current understanding of reconciling goals in diverse policy domains still lacks a holistic perspective: policymakers in silos are aiming to acknowledge policy domains that are directly affected by their interventions, but they might still overlook policy domains that are indirectly impacted [9]. In most cases, the coordination for policy integration occurs between two closely intertwined policy silos which limits identifying indirect and higher-order effects among interrelated domains. However, more indirect and higher-order effects among interrelated domains are less well studied, thereby influencing the success and pace of energy transitions.

To illustrate, the tax on natural gas is expected to stimulate the switch from natural gas across Europe [9,48]. On the one hand, the incremental tax on natural gas makes alternative heating more cost-effective [9], which corroborates current assumptions on the potential effect of these taxes. On the other hand, this tax also reduces the financial power of energy-poor households to invest in an alternative system [49] as well as legitimizing energy companies to benchmark the prices of alternative heating systems to the high price levels of natural gas [50], thereby reinforcing the mechanisms that reduce the pace of the switch out of natural gas [9]. Unless feedback effects are recognized, respective policymakers, who manage and govern the tax on natural gas, energy poverty, or pricing mechanisms in the energy market, might be unaware of the systemic implications caused by these interrelated policy subsystems. Consequently, a simple "tax on gas" does not necessarily lead to higher percentages of low-carbon heating in cities.

Notably, these (unintended) implications of feedback effects could arise over a long time horizon [7]. The influences from feedback mechanisms accumulate and reach a critical point [25,51], and only then do they reveal themselves as unintended systemic consequences [7,9]. To illustrate an example from the third chapter [7], the assumptions on "lower natural gas prices" by policymakers and scholars were only challenged over a long time frame when contradicting systemic data was gathered. The tipping point, specifically low prices for natural gas, activated another feedback mechanism, the fossil spill-over effect, and thus resulted in an unexpected and contradicting outcome: low natural gas prices lowered the coal prices more, thereby prolonging the coal electricity production in Europe. Scholars and policymakers might overlook how feedback mechanisms could change the system behavior over time unless they are explicitly investigating these longitudinal influences across the socio-technical system(s). This also implies that policymakers need to have sufficient levels of reflexive capacity to adapt to changes in socio-technical systems while designing policies [23,41,52].

Feedback effects in energy transitions generate continuous change. Dynamics emerge and develop as indirect, and often unexpected, responses to policy intervention for energy systems and transition policies [8]. The existence of feedback effects in energy transitions implies that policymakers should be aware and capable of addressing potential unintended repercussions from their decisions, reevaluate existing policy instruments and (potential) system responses, and redesign policy instruments in accordance with real-life evidence of socio-technical systems. All in all, simply responding to a change is not sufficient; it is also essential to be able to recognize systemic mechanisms behind unintended consequences during energy transitions [7]. Ultimately, policymakers have to be able to understand and analyze what different energy pathways could result in and recognize how and when to switch to new energy systems. This implies that the policy design should be a continuous effort where researchers, policymakers, experts, and communities evaluate and (re)adjust policies repeatedly at crucial milestones along the way. Thus, integrated policy-making [37] calls for a systems perspective where interdependent elements in the socio-technical system are analyzed and discussed with a range of experts from different silos [9]. Transition researchers underscore that employing co-creation approaches can reduce blind spots from fragmented policy-making [11,42], and group model building [44] can be useful at the policy (re)design phases to investigate these cross-sectoral effects [9].

To sum up, policy integration can be defined as the iterative policy-making process which enhances cross-functional collaboration and cooperation to adaptively redesign policy interventions in alignment with responses from the socio-technical system. This type of integration needs to factor in experimentation and learning during energy transitions [37,40]. This is important because there are simply no methods or models that can comprehensively predict the full extent of the complexity or uncertainty during energy transitions [7,9]. Therefore, learning from "less feasible" transition pathways and redesigning policies are necessary for achieving net-zero energy systems. Overall, policy integration calls for participative and systems approaches to ensure the strategic alignment between different governmental levels, influential actors, and interest groups for stimulating energy transitions toward a net-zero future.

Future research and practical implications

Transitioning into a net-zero energy system is a complex, continuous, and time-consuming task that requires multiple adjustments to cope with unexpected issues along the way. Developing integrated policies for energy transitions requires much more in-depth analysis and open discussions between scholars, policymakers, energy experts, and communities. Utilizing SD models in policy-making processes can identify blind spots and oversights due to interrelationships across policy subsystems [53,54] and underscore feedback mechanisms in policy domains that have not been discussed before. Qualitative SD models, especially using group model building, aids policymakers and scholars in identifying and recognizing implications of interdependencies and feedbacks in the socio-technical system. To illustrate, participative decision-making practices for Australian fisheries is a good example in practice [55] where long-term sustainability of and policy for fisheries are evaluated and decided with SD models in participative settings. SD models can help identify interrelated policy domains, conflict of interests, and reinforce and balance feedback effects for the transition under discussion [9]. Resulting models can help to evaluate policies' feasibility by considering the feedback mechanisms across the socio-technical system and interrelated policy domains [9].

The main premise of this thesis is that transitions are not linear [56]; thus, governing transitions does not proceed in a rational or deterministic manner [57]. Instead, institutions, cultures, and societal needs are intertwined while undergoing socio-technical change [15,58]. The real challenge is that institutions and energy systems need to co-evolve as a dynamic response to the contemporary behavior of the system [17]. Participative modeling approaches can be embedded in iterative policy-making steps or milestones to allow for learning from and responding to unexpected consequences during energy transitions. Notably, group model building workshops [59] can be utilized as a co-creation method [21,51] during the transition governance to collect inter-disciplinary knowledge from stakeholders, consider inter-silo influences, develop coherent policy instruments, assign coherent goals for policy silos, recognize the system's potential behaviors prior to policy implementation, and finally, to redesign policies in response to potential path-dependencies and feedback effects during energy transitions. In consequence, it is worthwhile to conduct more research on how to utilize (participative) modelling approaches to develop forward-facing policy-making processes for energy transitions.

(Re)designing policies is of utmost importance where scholars, policymakers, experts, and communities can come together to reduce the blind spots in transition policies [60]. Nonetheless, reflexive or adaptive governance also increases the resource allocation necessary for policy-making, which can prolong energy transitions or even lead to further conflicts of interest between policymakers and influential actors [45]. Policymakers are required to choose the correct spectrum concerning the sustainability targets and their respective deadlines. Understanding the complexity of transitions would allow adapting to the responses from the socio-technical system and reacting to them in a timely manner; however, this should not be at the expense of squandering valuable time to develop and implement policies for achieving net-zero targets [18,61]. Overall, more research is necessary for making transition governance process more agile, leaner, and swifter [56].

Limitations of the research

Disciplinary studies can provide certainty, accuracy, and precision to research questions that are more narrowly defined [7]. This also comes at the cost of overlooking interdependencies and feedback effects that can span across the socio-technical system [1]. This research did not deliberately set out to develop specific policy suggestions or solve specific transition problems, despite having a range of policy suggestions in each study [1,7,9]. Rather, it aspired to explore structures of feedback effects during energy transitions by synthesizing knowledge from disciplinary studies with an interdisciplinary lens [62]. As highlighted in **1.4. System dynamics notation**, this thesis has made a conscious choice for qualitative models to ensure the broad boundary necessary to investigate transition policies as an endogenous part of energy transitions, which allowed this work to explore feedback effects in energy systems and policies. Advancing the findings from this study and building quantitative models on the foundations of this research might bring novel insights for transitions and allow further analysis and evaluation of transition policies. A broad research scope also implies a trade-off concerning the depth of the study [1]. This also implies that there could be other disciplinary studies that have contrasting claims to the feedback effects discussed in this work. Although the implications of feedback effects in energy transitions are very hard to conceptualize in an exhaustive manner, it is still essential to explore and discuss them in interdisciplinary studies, such as this thesis, because this endeavor will aid policymakers and scholars in recognizing systemic effects caused by interrelated policy domains and thus support the reconciliation of policy silos.

The limitations for modeling often revolve around the level of abstraction and translating conceptual elements from different disciplines into a coherent formal language [51]. The level of abstraction in a modeling study greatly influences the scope of the research [51]. This translation process almost always involves assumptions about the perceptions and worldviews of stakeholders and researchers [51]. Feedback effects are perceived and experienced differently by each stakeholder; thus, it is virtually impossible to comprehensively model each potential perception of interdependencies [9]. This also implies that each model represents a static and aggregated snapshot of the whole system [63]. In reality, the socio-technical system dynamically changes and feedbacks are (re)formed as a response to an accumulation of actor actions and system responses [7]. The aim of this thesis was never to model a comprehensive or exhaustive model of feedback effects in transitions, but rather to demonstrate that qualitative system dynamics modeling can support policy integration processes by recognizing feedback mechanisms that lead to unintended policy consequences [1,7,9].

Although SD modeling approaches are a powerful tool to explore and analyze interconnectedness [64], transition challenges are not limited to aspects of interconnectedness. Investigating uncertainty or power dynamics in energy transitions require other systems approaches that can better tackle these issues than SD models [25,51]. This thesis explored and discussed the conflict of interests or power dynamics to a certain extent with SD models (e.g. ongoing negotiation tactics between the Dutch government and energy companies in the fifth chapter [65]); nonetheless, the uncertainty during transitions was outside the scope of this research. Although this thesis still argues the value of (participative and continuous) qualitative modeling in dealing with interdependencies, it is essential to note that the complexity in transitions cannot simply be boiled down to feedback effects. For example, uncertainties and potential disruptions to the system could be overlooked with this method (e.g. DeepSeek's unexpected emergence at Trump's inauguration date which significantly shorted the stock prices for US-based AI companies). Although this thesis still argues that qualitative modeling methods are well-equipped to handle structural and contemporary couplings in system structures and thus reveal strong-weak spots in transition policies, there are still better methods to handle the uncertain, disruptive, delayed, or probabilistic nature of complexity. To illustrate, loop dominance is an essential concept in quantitative SD modeling which analyzes how certain feedback loops behave under different scenarios. Although this thesis intrinsically handled such scenarios in its chapters (e.g. Chapter 3 conditions for fossil spillover), simulation assistance or quantitative models could help researchers and policy-makers to test and evaluate their assumptions and the potential outcomes for discussed socio-technical transitions.

Concluding remarks

This thesis elucidated key aspects of feedback effects that are embedded in energy transitions through a series of explorative qualitative modeling studies [66]. The thesis findings underline a critical role for scholars and policymakers in considering the complexity that feedback effects bring to the policy-making processes during energy transitions. Recognizing feedback effects in energy transitions is a dynamic challenge. In other words, policymakers are challenged to adopt a reflexive review capacity to continuously (re)consider the assumptions and expected impact of their decisions at crucial transition milestones. In light of this review, policymakers are challenged again, this time, to adapt and redesign policies in consideration of interdependencies and feedback effects during energy transitions.

Qualitative SD models promote interdisciplinary communication and collaboration between scholars, policymakers, and energy experts by building a shared understanding of how pathway(s) for future energy systems, unintended responses to policy interventions, and feedback effects could emerge during transitions. Utilizing SD models can reveal the impact of feedback effects across different policy subsystems, prepare policymakers to respond to complex system behavior, take on a broader systemic perspective which spans across multiple policy domains and subsystems, and thus stimulate integrated policy-making for energy transitions. That being said, the reconciliation of ambitions from silos is a continuous effort because policy silos are necessary mechanisms to break down the complexity of systems, and thus, they can never be broken down completely. All in all, balancing effective resource management and policy integration is one of the major challenges that transition scholars need to investigate further.

As the world advances towards net-zero energy systems, it is imperative to continue to explore and address the complexity of interconnectedness that is embedded in energy transitions. Reconciling policy silos is one of the most challenging tasks in transition governance, but it is also one of the most essential. Policy integration for energy transitions requires a holistic lens which considers stakes and influences from interdependent policy domains and subsystems. This thesis paves the way forward for future research and practical applications by employing and promoting system dynamics modeling to explore and address feedback effects for developing forward-facing methods toward a net-zero future.

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Research data management

Data processing

The primary data described in my thesis have been collected with the consent of participants. Privacy-sensitive data have been pseudonymized. Existing data collected by others have been obtained legitimately. The secondary data described in my thesis are comprised of open-access online documents which present no conflict of interest and scientific articles which cannot be shared publicly due to copyright restrictions.

Data Storing

During research, privacy-sensitive data (e.g. transcripts/recordings of interviews and workshops or analyzed qualitative data/quotations from scientific articles which are not open-access) have been stored on a password-protected computer. The research data will be archived at the Radboud Data Repository under a private folder which can only be accessed via the researcher or advisors of the research to ensure the integrity of the thesis. After completion of my PhD, research data will be securely stored for reasons of scientific integrity for at least 10 years at the Radboud Data Repository.

During the research, data that were suited to be made openly available (e.g. documents which were open access, coding from open–access data, resulting models, literature review filter/selection process, etc.) were already published in Mendeley Data Folders along with published scientific articles. The links for the Mendeley data folders are shared below.

Article 1:

- **Name:** Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent insights from the Netherlands
- **Article Link:** https://doi.org/10.1016/j.cities.2023.104397
- **Mendeley Link:** https://data.mendeley.com/preview/r95hxbfvb8?a=7e8063f1-7df3-4789-8f46-da6d1f7e381f

Article 2:

- **Name:** The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition?
- **Article Link:** https://doi.org/10.1016/j.rser.2020.110552
- ***Data not shared due to copyrights of quotations from the literature.***

Article 3:

- **Name:** District heating with complexity: Anticipating unintended consequences in the transition towards a climate-neutral city in the Netherlands
- **Article Link:** https://doi.org/10.1016/j.erss.2024.103450
- **Mendeley Link:** https://data.mendeley.com/preview/f8nwdjvhpf?a=b1eab500-1c11-4e96-aea2-a54f7380a954

Article 4:

- **Name:** Feedbacks in energy transition governance: a systems analysis of European district heating policies Netherlands
- **Article Link:** Publication Submission/Review in Progress
- **Mendeley Link:** https://data.mendeley.com/preview/z4mmgzpmvv?a=7cc402b9-6996-4ff8-8f78-85981dea91b4

Data re-use

In my project, I cannot make part of the data publicly available after research due to legal reasons for ownership of secondary data (documents which were not open-access) and the privacy of respondents. However, the collected and analyzed data which were open-access were already shared in Mendeley data folders. The links to these open-access data can be found above.

Anonymized data are stored together with the necessary documentation in the Radboud Data Repository to which access is prohibited. It is not possible to link data to individuals (unless explicit consent has been given) in publications or published datasets.

Summary

This thesis explored the implications of feedback effects in energy transitions to encourage policymakers and researchers to recognize and address these complex mechanisms. To achieve that, each article investigated the most influential and debated issues which involve feedback effects in different energy transitions. Each chapter built on the suggestions and shortcomings of previous chapters, which advances step-by-step toward answering the main research question: What are the feedback effects that affect energy transitions and their governance? Although the research questions tackled in individual chapters may seem isolated at first sight due to the topic's complexity, this thesis employed a progressive and coherent build-up by starting from socio-technical interdependencies in the second chapter and reaching feedback effects in energy systems and transition policies in the fifth chapter. The narrative progression of this thesis and the dimensions of the included studies are summarized and explained in **Table 1**.

The second chapter [7] built the theoretical conceptualization to elaborate on different types of interdependencies between urban energy infrastructures in Dutch cities. This chapter explored and elaborated on the role of interdependent infrastructure systems, by investigating socio-technical interdependencies among 25 distinct technologies from the electricity, heat, and mobility sectors, thereby explaining how these socio-technical interdependencies between energy infrastructures influence sustainability efforts in cities. This chapter distinguished seven socio-technical interdependency types that are relevant for energy transitions: functional, evolutionary, spatial, life-cycle, policy/procedural, market, and culture/norm interdependencies. The results from the second chapter offered an interdisciplinary framework to explore, understand, and discuss interdependencies and their implications for energy transitions in later chapters [6,33].

The third chapter [7] investigated the role of natural gas as a transition fuel in the electricity sector on a global scale to explain how interdependencies influence the switch from coal generation to intermittent solar and wind energy [67]. This chapter highlighted that feedback effects in the electricity sector are responsible for the ongoing debates [7]. To draw this conclusion, this research synthesized knowledge from different sides of the debate to explain how feedback effects influence the transition toward renewable power generation. The main premise behind the ongoing debates is that natural gas can replace power generation by coal to reduce emissions, and then open up the pathway for intermittent renewable technologies such as solar and wind. Although scientists agree that

natural gas can achieve emission reduction by replacing coal generation, feedback effects among energy systems can also divert future investments from solar and wind energy unless certain precautions are taken by policymakers [7]. This chapter advanced the ongoing debate on using natural gas as a transition fuel by exposing how the positive and negative effects of energy transitions are interdependent via feedback mechanisms. The resulting models indicated that positive immediate and local benefits of natural gas also lead to unwanted long-term and global effects which can work against energy transitions and net-zero targets. In consequence, this research suggested policymakers and scholars consider the impact of feedback effects in an integrated manner by considering multiple energy systems' co-evolution over a long-time horizon across different regions.

The fourth chapter [9] investigated the role of district heating systems in Rotterdam to explore how feedback effects in the urban heat sector influence the pace of the energy transition. District heating systems, are considered a viable option to replace natural gas in high-density cities for reducing urban emissions such as Rotterdam [48,68]. This chapter explores socio-technical interdependencies on an urban scale to highlight and explain how feedback mechanisms are influential for and influenced by their local context [13]. To explore the local context, this research also collected primary data by conducting participative model-building workshops, namely the Group Model Building, with stakeholders in Rotterdam to investigate the switch from natural gas to district heating systems. Together with a diverse set of stakeholders, this study explored both technologically oriented and policy-oriented insights to reveal how socio-technical interdependencies influence district heating transitions in Rotterdam. The results from this chapter illustrated that the pace of energy transitions will slow down if policymakers focus too much on technological availability and design policies on the available technological pathways. Consequently, each transition project requires a tailor-made solution that can recognize socio-technical interdependencies and potential feedback effects for that local context.

The fifth chapter [14] explored district heating transitions by broadening the geographical scale and time frame [7]. This chapter zoomed out to a larger geographical area and a longer time frame as the third chapter suggested continuing investigation on district heating transitions [7]. This chapter began with an exploration of the influence of the 1973 oil crisis on the development of district heating systems (also natural gas) across different European regions. The fifth chapter maps out how feedback mechanisms are (re)formed in and *between* energy systems and transition policies throughout the transition governance process [15] by highlighting the mechanisms that bridge the energy policies, disciplinary actors, and consequential change in energy technologies.

The sixth chapter concludes that recognizing feedback effects in energy transitions is a dynamic challenge. In other words, policymakers should be reflexive enough to review the impact of their decisions at crucial transition milestones; then, they have to adapt and redesign policies while considering interdependencies and feedback effects during energy transitions. Qualitative SD models promote interdisciplinary communication and collaboration between scholars, policymakers, and energy experts by building a shared understanding of how pathway(s) for future energy systems, unintended responses to policy interventions, and feedback effects could emerge during transitions.

Table 1 - Dimensions of the articles included in this thesis

No	Article Name	Scope	Location	Energy Sector	Contrast	Relevance and Content	Included Energy Technologies
1	Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent insights from the Netherlands	National	the Netherlands	Electricity, Heat, Mobility	Conceptual research on recognizing socio-technical interdependencies	I introduced the existence and mechanisms of interdependencies in (socio-technical) energy systems which worked as an interdisciplinary framework and boundary for future studies.	Solar - Power, Wind, Biomass - Power, Natural gas - Power, Smart Grids, Electric Batteries, Hydrogen Electrolysis, Hydrogen Storage, Biogas Injection - Heat, Hydrogen Injection - Heat, Heat Pump - Individual, Heat Pump - Central, Biomass - Heat, Aquathermal, Geothermal, Residual Heat, District Heating, Solar - Heat, Heat Storage, Biofuel - Mobility, Hydrogen - Mobility, Electric Car Batteries, Fossil Fuel - Mobility
2	The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition?	Global	-	Electricity	Modeling study on in the electricity sector to highlight global systemic effects	I zoom out and demonstrate that unwanted system behaviors (indirect and long-term consequences) are often caused as a result of feedback effects by investigating the use of natural gas as a transition fuel in the global power sector.	Natural gas, Coal, Solar - Power, Wind, Carbon Capture Storage and Utilization
3	District heating with complexity: Anticipating unintended consequences in the transition towards a climate-neutral city in the Netherlands	City	Rotterdam	Heat	Modeling study in the heat sector to highlight systemic effects from local contexts	I zoomed in on an urban district heating transition in Rotterdam and utilized Group model building approach to explore and explain how feedbacks are influenced by their local contexts.	Natural gas, District Heating, Geothermal, Aquathermal, Combined Heat and Power, Residual heat, Waste-to-Energy, Carbon Capture Storage and Utilization
4	Feedbacks in energy transition governance: a systems analysis of European district heating policies	Continental /Global	Europe	Heat	Modeling study in the heat sector to synthesize global/local effects for district heating systems	I zoom out again on Europe and investigate district heating transitions at a longer-time period across different regions to conceptualize the interdependencies and feedbacks between energy systems and transition policies.	Natural gas, Coal, Oil, Combined Heat and Power, Biomass, Waste-to-Energy, Geothermal, Residual

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Samenvatting

Deze dissertatie onderzocht de implicaties van feedback effecten in energietransities om beleidsmakers en onderzoekers aan te moedigen deze complexe mechanismen te herkennen en aan te pakken. Om dat te bereiken onderzocht elk artikel de meest invloedrijke en bediscussieerde kwesties waarbij feedbackeffecten een rol spelen in verschillende energietransities. Elke studie bouwde voort op de suggesties en tekortkomingen van voorgaande hoofdstukken, waardoor stap voor stap vooruitgang werd geboekt bij het beantwoorden van de belangrijkste onderzoeksvraag: Wat zijn de feedbackeffecten die energietransities en hun besturing beïnvloeden? Hoewel de onderzoeksvragen die in de afzonderlijke hoofdstukken worden behandeld op het eerste gezicht geïsoleerd lijken vanwege de complexiteit van het onderwerp, heeft dit proefschrift een progressieve en coherente opbouw gebruikt door te beginnen bij socio-technische onderlinge afhankelijkheden in de eerste studie en uit te komen bij feedback effecten in energiesystemen en transitiebeleid in de laatste studie. Het narratieve verloop van dit proefschrift en de dimensies van de opgenomen studies worden samengevat en toegelicht in Tabel 1 op de vorige pagina.

Het tweede hoofdstuk [26] bouwde aan de theoretische conceptualisatie om verschillende typen onderlinge afhankelijkheden tussen stedelijke energie-infrastructuren in Nederlandse steden uit te werken. Deze studie onderzocht en werkte de rol van onderling afhankelijke infrastructuursystemen uit door socio-technische afhankelijkheden te analyseren tussen 25 verschillende technologieën uit de elektriciteits-, warmte- en mobiliteitssectoren. Zo werd uitgelegd hoe deze socio-technische afhankelijkheden tussen energie-infrastructuren inspanningen voor duurzaamheid in steden beïnvloeden. Dit hoofdstuk onderscheidde zeven typen socio-technische afhankelijkheden die relevant zijn voor energietransities: functionele, evolutionaire, ruimtelijke, levenscyclus-, besturing/procedurele, markt-, en cultuur/norm-afhankelijkheden. De resultaten van de eerste studie boden een interdisciplinair kader om afhankelijkheden en hun implicaties voor energietransities in latere hoofdstukken te verkennen, te begrijpen en te bespreken [34,74].

Het derde hoofdstuk [26] onderzocht de rol van aardgas als transitiebrandstof in de elektriciteitssector op mondiale schaal om uit te leggen hoe afhankelijkheden de overstap van kolengeneratie naar intermitterende zonne- en windenergie beïnvloeden [75,76]. Deze studie benadrukte dat feedbackeffecten in de elektriciteitssector verantwoordelijk zijn voor de voortdurende debatten [26]. Om tot deze conclusie te komen, heeft het onderzoek kennis uit verschillende

standpunten in het debat samengebracht om te verklaren hoe feedbackeffecten de transitie naar hernieuwbare stroomopwekking beïnvloeden. De belangrijkste aanname achter de lopende debatten is dat aardgas stroomopwekking door kolen kan vervangen om emissies te verminderen en daarmee de weg vrijmaakt voor intermitterende hernieuwbare technologieën zoals zonne- en windenergie. Hoewel wetenschappers het erover eens zijn dat aardgas emissiereductie kan bereiken door kolengeneratie te vervangen, kunnen feedbackeffecten tussen energiesystemen toekomstige investeringen in zonne- en windenergie afleiden, tenzij beleidsmakers bepaalde voorzorgsmaatregelen treffen [26,78]. Dit hoofdstuk bracht het lopende debat over het gebruik van aardgas als transitiebrandstof verder door te laten zien hoe de positieve en negatieve effecten van energietransities onderling afhankelijk zijn via feedbackmechanismen. De resulterende modellen lieten zien dat de positieve, directe en lokale voordelen van aardgas ook leiden tot ongewenste, lange termijn- en mondiale effecten die tegen energietransities en net-zero ambities kunnen werken. Als gevolg hiervan suggereerde dit onderzoek dat beleidsmakers en onderzoekers de impact van feedbackeffecten op een geïntegreerde manier zouden moeten beschouwen, waarbij rekening wordt gehouden met de co-evolutie van meerdere energiesystemen over een lange tijdshorizon en in verschillende regio's.

Het vierde hoofdstuk [18] onderzocht de rol van warmtenetwerken in Rotterdam om te verkennen hoe feedbackeffecten in de stedelijke warmtesector het tempo van de energietransitie beïnvloeden. Warmtenetwerken worden beschouwd als een haalbare optie om aardgas te vervangen in dichtbevolkte steden, zoals Rotterdam, om stedelijke emissies te verminderen [6,32]. Dit hoofdstuk onderzoekt socio-technische afhankelijkheden op stedelijke schaal om te benadrukken en uit te leggen hoe feedbackmechanismen van invloed zijn op, en beïnvloed worden door, hun lokale context [82]. Om de lokale context te verkennen, verzamelde dit onderzoek ook primaire data door participatieve modelbouwworkshops te organiseren, namelijk Group Model Building, met belanghebbenden in Rotterdam om de overstap van aardgas naar warmtenetwerken te onderzoeken. Samen met een diverse groep stakeholders onderzocht deze studie zowel technologisch georiënteerde als beleidsmatige inzichten om aan te tonen hoe socio-technische afhankelijkheden van invloed zijn op de transitie naar warmtenetwerken in Rotterdam. De resultaten van dit hoofdstuk toonden aan dat het tempo van energietransities vertraagt als beleidsmakers te veel nadruk leggen op technologische beschikbaarheid en beleid ontwerpen op basis van de beschikbare technologische trajecten. Daarom vereist elk transitieproject een op maat gemaakte oplossing die rekening houdt met de specifieke socio-technische afhankelijkheden en mogelijke feedbackeffecten binnen die lokale context.

Het vijfde hoofdstuk onderzocht de transities naar warmtenetwerken door de geografische schaal en tijdshorizon te verbreden [26]. Dit hoofdstuk zoomde uit naar een groter geografisch gebied en een langere tijdsperiode, zoals de tweede studie suggereerde, om verder onderzoek naar warmtenettransities voort te zetten [26]. Het hoofdstuk begon met een verkenning van de invloed van de oliecrisis van 1973 op de ontwikkeling van warmtenetwerken (en ook aardgas) in verschillende Europese regio's. De laatste studie brengt in kaart hoe feedbackmechanismen worden (her)gevormd binnen en tussen energiesystemen en transitiebesturing gedurende het proces van transitiebeleid [51]. Hierbij worden de mechanismen benadrukt die een brug slaan tussen energiebeleid, disciplinaire actoren en de daaruit voortvloeiende veranderingen in energietechnologieën.

Het zesde hoofdstuk concludeert dat het erkennen van feedbackeffecten in energietransities een dynamische uitdaging is. Met andere woorden, beleidsmakers moeten voldoende reflexief zijn om de impact van hun beslissingen te evalueren op cruciale overgangsmomenten; vervolgens moeten zij beleid aanpassen en herontwerpen, rekening houdend met afhankelijkheden en feedbackeffecten tijdens energietransities. Kwalitatieve systeem dynamische modellen bevorderen interdisciplinaire communicatie en samenwerking tussen wetenschappers, beleidsmakers en energie-experts door een gedeeld begrip te creëren van hoe paden voor toekomstige energiesystemen, onbedoelde reacties op beleidsmaatregelen en feedbackeffecten kunnen ontstaan tijdens transities.

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About the author

Cem Gürsan was born in Izmir Turkey in 1987. In 2010, Cem obtained a bachelor's degree in Information Systems Engineering from the dual diploma program led by Binghamton University, USA, and Bogazici University, Turkey. In 2014, Cem received his master's degree in business administration at Galatasaray University with Cum Laude. He worked as a project manager at Klimak Ltd., a mechanical engineering company that specializes in energy projects involving heating, ventilation, and air conditioning systems. His passion and interest in energy systems led him to the Master of Science in Business Analysis and Simulation Modeling program at Radboud University, where he graduated in 2019 with cum laude. Between 2020 and 2024, he worked on the INSpECT research project. Since 2024 August, he has been working as a post-doctoral researcher at Radboud University to develop a quantitative model for low-carbon lifestyles. For his work, Cem uses modeling approaches to explore the complexity caused by interdependencies between energy systems to conclude potential energy pathways toward a sustainable future.

His research has been well received by a wide range of audience including scholars, policymakers, and energy experts. Notably, his work on using natural gas as a transition fuel has been cited and commended by many international organizations such as the International Monetary Funds, the United Nations Framework Convention on Climate Change, the Australian Parliament, the Italian Ministry of Foreign Affairs, and more. He contributed to extra-curricular research activities at the Methodology Department by co-authoring a research article on how to use qualitative system dynamics modeling in sustainability challenges and authoring a book chapter with Sara Gonella and Dr. Vincent de Gooyert for Edward Elgar Publishing (under consideration) on how to utilize qualitative system dynamics models and integrative reviews together for exploring and addressing sustainability challenges. During his academic work, Cem has been teaching research and modeling methodologies to master's and bachelor's students and conducted participative modeling workshops with policymakers, experts, and students in different settings.

In the future, Cem aims to keep exploring and addressing the complexity of designing sustainable energy systems and governing their transitions.

List of academic publications

1) Gürsan, C., & de Gooyert, V. (2021). The systemic impact of a transition fuel: Does natural gas help or hinder the energy transition? *Renewable and Sustainable Energy Reviews*, 138, 110552. https://doi.org/10.1016/j.rser.2020.110552
2) Gürsan, C., de Gooyert, V., de Bruijne, M., & Rouwette, E. A. J. A. (2023). Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent insights from the Netherlands. *Cities*, 140, 104397. https://doi.org/10.1016/j.cities.2023.104397
3) Gürsan, C., de Gooyert, V., de Bruijne, M., & Raaijmakers, J. (2024). District heating with complexity: Anticipating unintended consequences in the transition towards a climate-neutral city in the Netherlands. *Energy Research & Social Science*, 110, 103450. https://doi.org/10.1016/j.erss.2024.103450
4) de Gooyert, V., Awan, A., Gürsan, C., Swennenhuis, F., Janipour, Z., & Gonella, S. (2024). Building on and contributing to sustainability transitions research with qualitative system dynamics. *Sustainability Science*, 19(6), 1949-1962. https://doi.org/10.1007/s11625-024-01548-9
5) Gürsan, C., de Bruijne, M., & de Gooyert, V., (2024). Feedbacks in district heating systems and transition policies: A systems analysis of net-zero district heating transitions in Europe. *Energy Reports*, https://doi.org/10.1016/j.egyr.2024.11.067
6) Gürsan, C., Gonella, S., & de Gooyert, V., (under review). Keeping it complex; advancing sustainability debates through complexity-based integrative reviews. In Rouwette, E. & Hafeez, B., *Methodology to Address Grand Challenges: Theory, Practice and Interventions*. Cheltenham, UK: Edward Elgar Publishing

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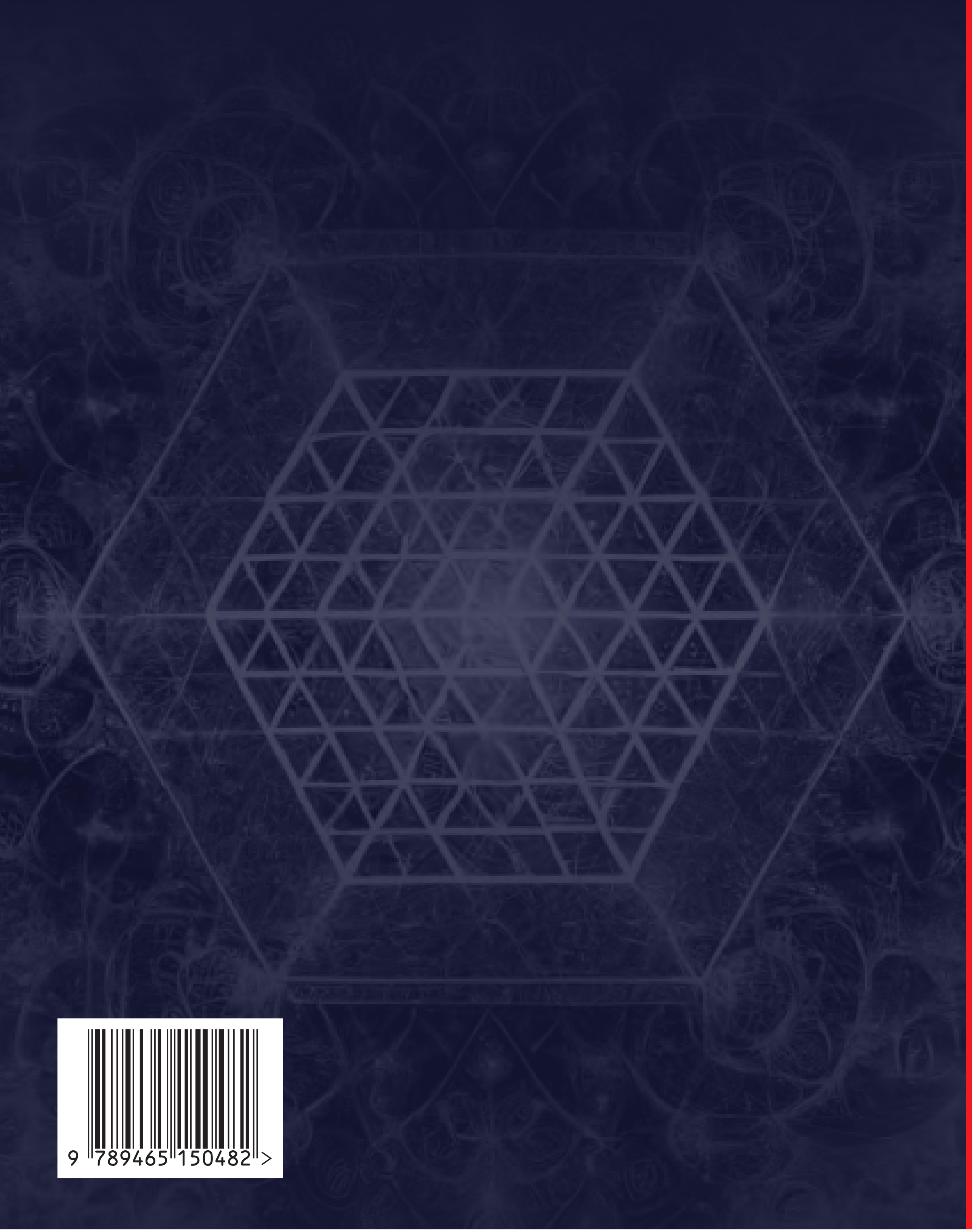
Finally, I would like to dedicate this work to my daughter, Ida Gürsan, since all of the effort that I put in the name of sustainable energy is just a father's commitment and perseverance for creating his child a cleaner, more just, and happier world.



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