District heating with complexity

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Original research article

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

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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 modeling provides policymakers 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.

1. 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

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Abbreviations: **B**, Balancing feedback loop; **R**, Reinforcing feedback loop; **CCS**, Carbon Capture and Storage; **CCU**, Carbon Capture and Utilization; **SD**, System Dynamics; **GMB**, Group Model Building.

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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.

2. Theoretical background

2.1. 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].

2.2. 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].

We illustrate two different types of feedback effects with two examples. Fig. 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

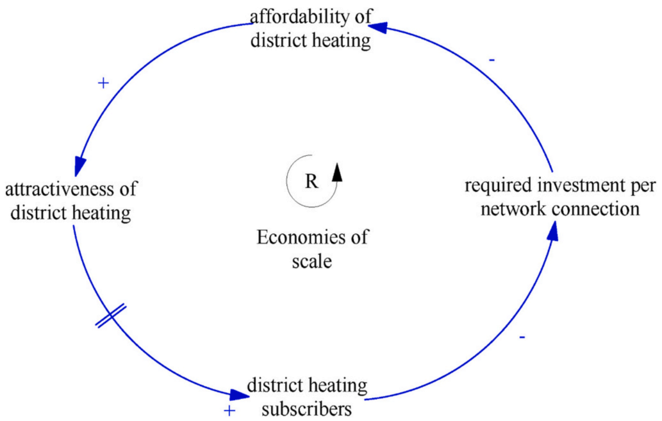

Fig. 1. Example of reinforcing feedback. Arrows indicate causal connections. An increase in one variable leads to an increase (+) or decrease (−) of the next variable, sometimes with a delay (||).

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 Fig. 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.

Fig. 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].

The 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 modeling techniques.

3. 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 Fig. 3, on the transition from natural gas heating to district heating in Rotterdam. Our data collection consisted of an iterative data 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, as shown in Table 2. 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.

3.1. 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

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[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.

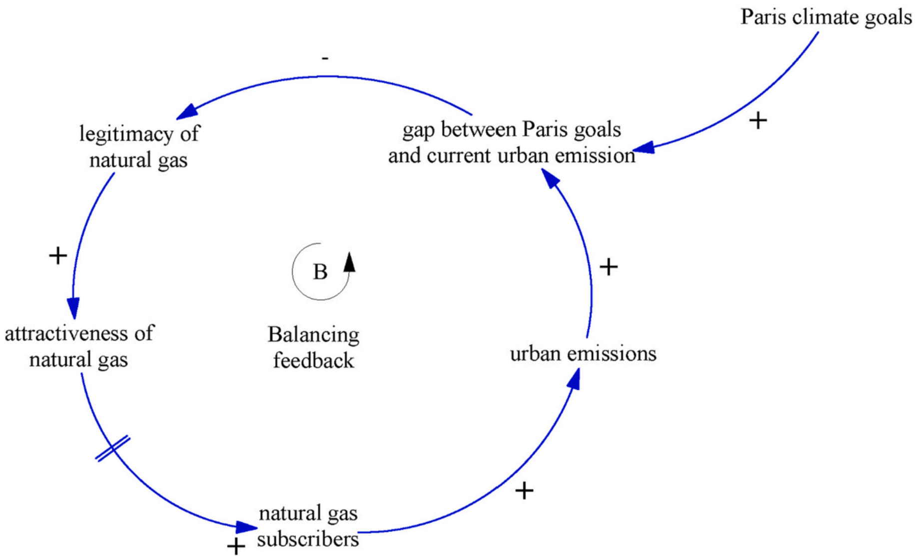

Fig. 2. Example of balancing (B) feedback. Arrows indicate causal connections. An increase in one variable leads to an increase (+) or decrease (−) of the next variable, sometimes with a delay (||).

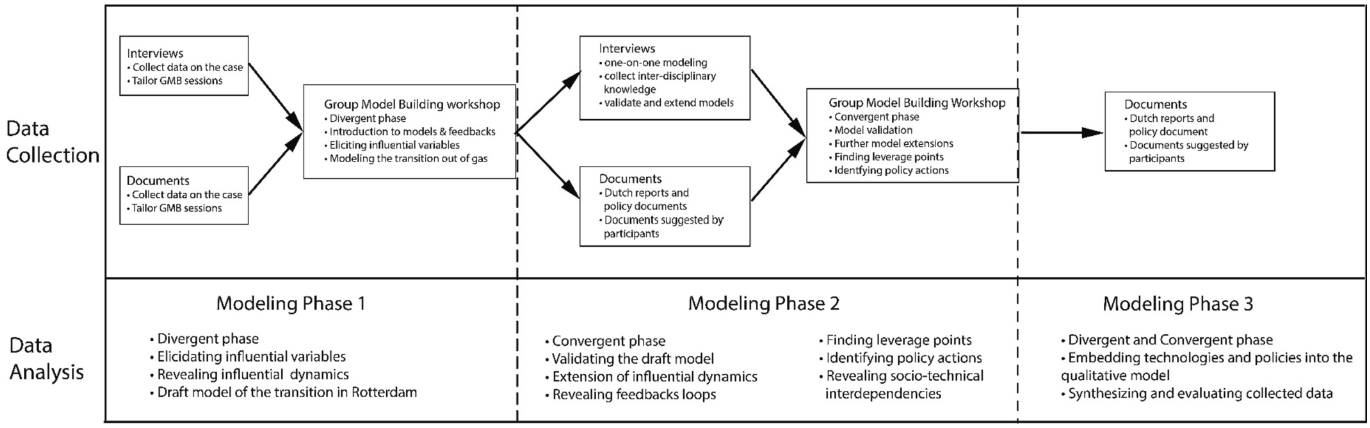

Fig. 3. Data collection and analysis methods used in the Rotterdam case, shown in a flow chart.

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

urban transitions in unique ways in every city [39]. As Figs. 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

Table 2
List of documents reviewed for the case study.

Document name	Description	Publishing organization	Privacy	Page number	Link
Final report on area exploration for natural gas-free Rotterdam North	Final report on the Rotterdam Noord's transition plans that focuses on the building, social, technical, business case, and schedule analysis.	Rotterdam municipality	Confidential document	121	Confidential
Environmental vision Rotterdam	Integral assessment of urban plans that includes but not limited to: future-proof neighborhoods, natural gas-free transition, climate adaptation, greening, clean air and the replacement of the sewer.	Rotterdam municipality	Public document	173	(Rotterdam Municipality, 2021)
Rotterdam transition vision for heating	Heat Transition Vision describes why Rotterdam municipality wants the transition, what the plans are and when and how Rotterdam municipality wants to implement these plans.	Rotterdam municipality	Public document	41	(Rotterdam municipality, 2021)
Rotterdam Climate agreement	Rotterdam climate agreement aligns the Dutch climate agreement with the Rotterdam's transition plans in a step by step manner	Rotterdam municipality	Public document	44	(Rotterdam Climate Alliance, 2019)
Eneco One planet	Eneco is the DHN provider for the Rotterdam. This report mentions the climate goals of Eneco	Eneco	Public document	43	(Eneco, 2021)
Aedes Compensation Table	Aedes is the overarching organization for Dutch housing associations. This compensation table gives information on potential rent increases due to insulation work.	Aedes	Public document	13	(AEDES, 2021)
National Insulation Program	This report gives information on the current policies to subsidize insulation in the Dutch built environment	Ministry of the Interior and Kingdom Relations	Public document	30	(MBZK, 2022)
Policy program for sustainable urban environment	This report gives information on the policies that aim to make the Dutch built environment sustainable.	Ministry of the Interior and Kingdom Relations	Public document	33	(de Jonge, 2022)
Facts about energy poverty in the Netherlands	This report gives information on the energy poverty in the Netherlands.	TNO	Public document	9	(Mulder et al., 2021)
Master Plan Geothermal Energy in the Netherlands	This report gives information about the future plans for geothermal energy in the Netherlands	Platform Geothermie	Public document	70	(TNO, 2018)
Potential Geothermal energy in the Zuid-Holland	This report gives information about the future plans for geothermal energy in the Zuid-Holland region	Zuid-Holland province	Public document	64	(Buik et al., 2016)
From residual heat to useful heat in the Rijnmond	This report gives information about the residual heat potential in the Rijmond region which is within Zuid-Holland, very close to the Rotterdam.	Delft University	Public document	64	(Rooijers, 2002)
National Roadmap Residual heat	This report gives information about the residual heat potential in the Netherlands	Delft University	Public document	148	(Schepers & van Lieshout, 2011)delft
Developments of heat distribution networks in NL	This report gives information about the developments in DHNs in the Netherlands	ECN	Public document	72	(ECW, 2021)

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.

3.2. 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 h 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.

3.3. 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.[2] 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].[3]

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.

4. 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].

4.1. National strategy to replace gas with district heating

Fig. 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 Fig. 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.

4.2. A systemic trap while replacing gas: Energy-poverty

Fig. 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 Fig. 5. Energy companies can distribute gas for their remaining customers until 2050 [55]. In the long run, energy companies will lose 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**,

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[2] 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].

[3] 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].

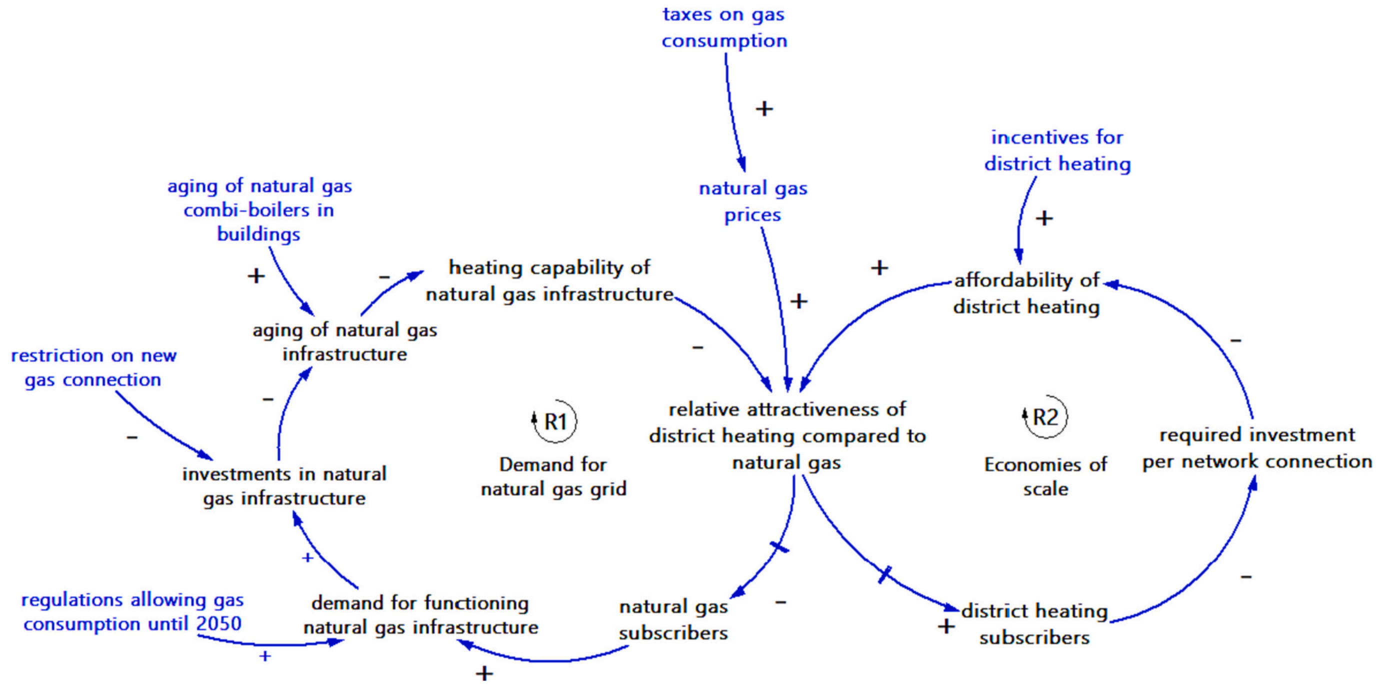

Fig. 4. National policy of the Netherlands to replace natural gas in the built environment, represented by two reinforcing feedback loops R1 and R2.

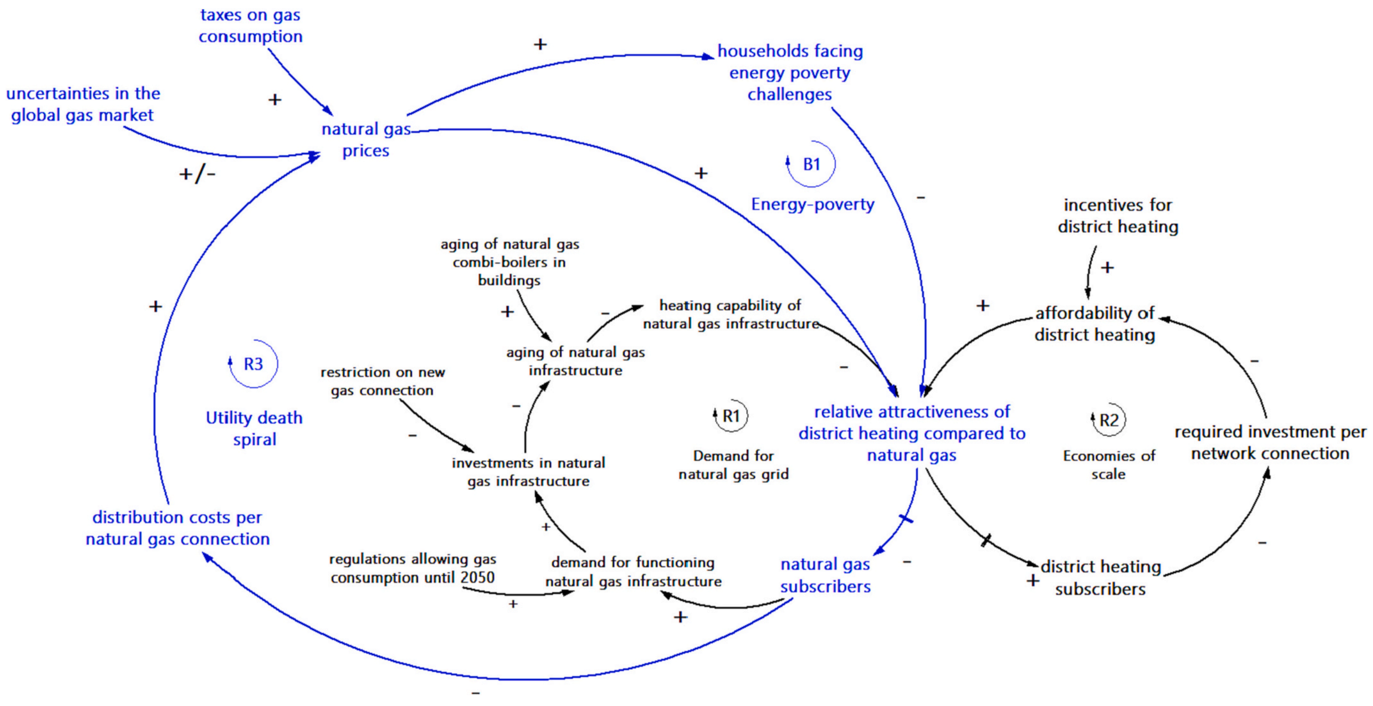

Fig. 5. Energy-poverty caused by increasing natural gas prices can obstruct the transition out of gas.

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.

4.3. 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]. Fig. 6 shows the policy to accelerate the transition away from natural gas towards district heating.

The collaboration with housing associations reinforces the benefits from economies of scale in district heating, forming an addition to **R2** in Fig. 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**).

4.4. 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.

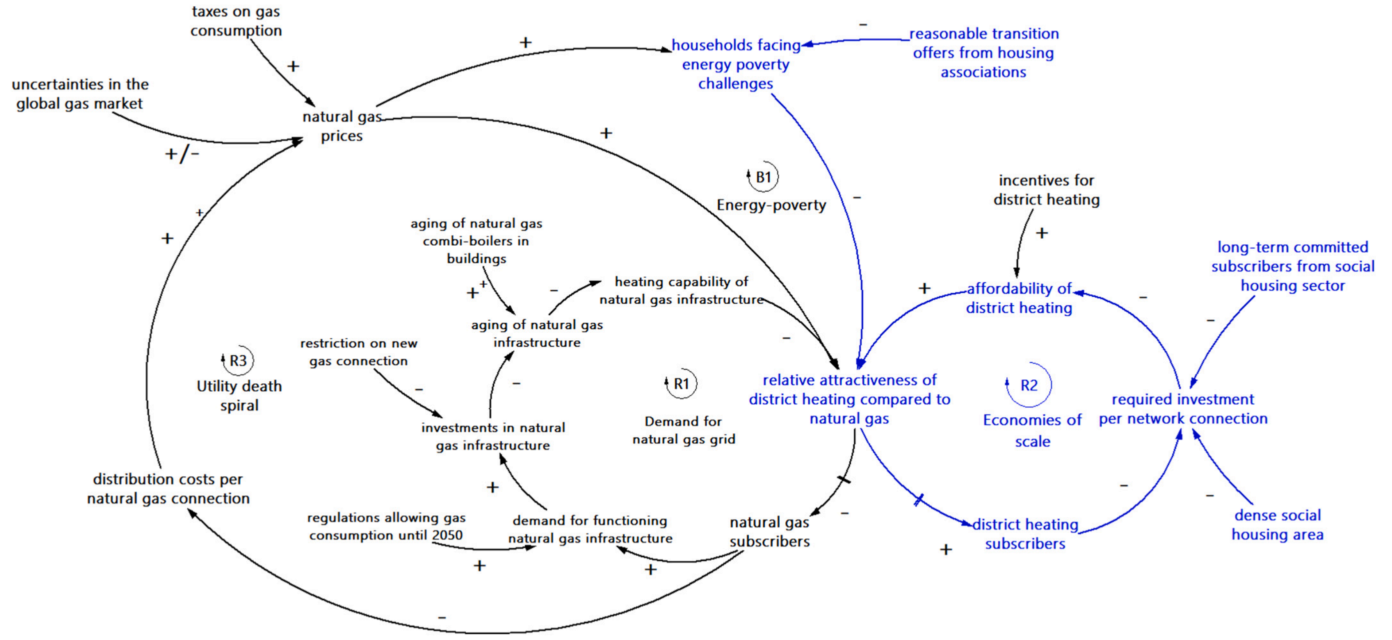

Fig. 6. Housing associations accelerate the adoption of district heating systems.

4.5. First phase: Expanding the network

Fig. 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.

4.6. Second phase: Energy-efficiency and renewable integration

Fig. 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.

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[4] [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.[5] Notably, focusing on a two-phased transition can significantly mitigate emissions leading up to 2030. However, Fig. 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.

4.7. 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. Fig. 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

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[4] 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).

[5] Below we outline the feedback loops that represent the discussed mechanisms.First phase:(R2) Expansion of the heat network(R4) Expansion of the heating systemSecond phase:(R5) Investments in the energy-efficiency of the network(R6) investing in and utilizing low-carbon heating systemsFig. 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).

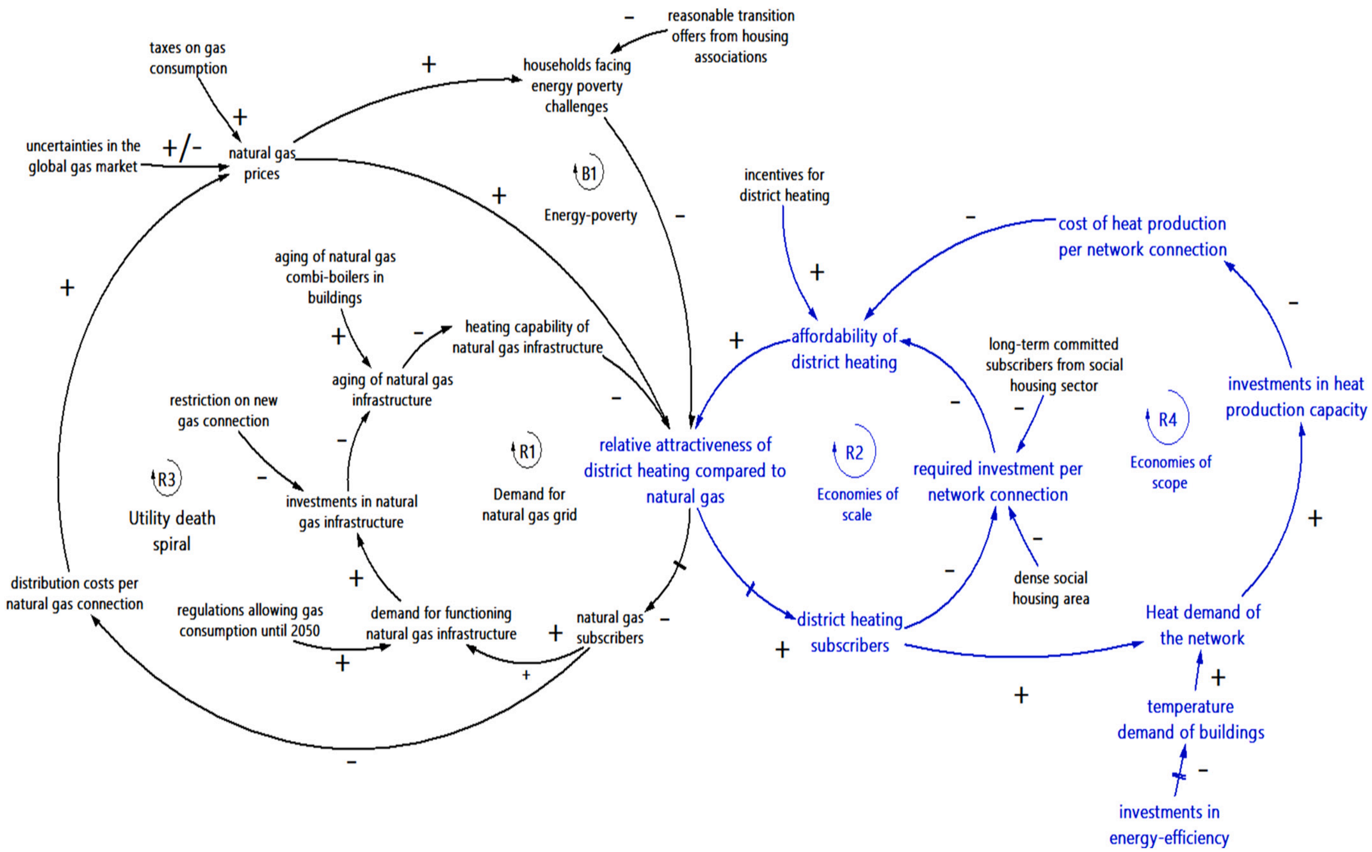

Fig. 7. The first phase of the transition plan: the expansion of the heat network.

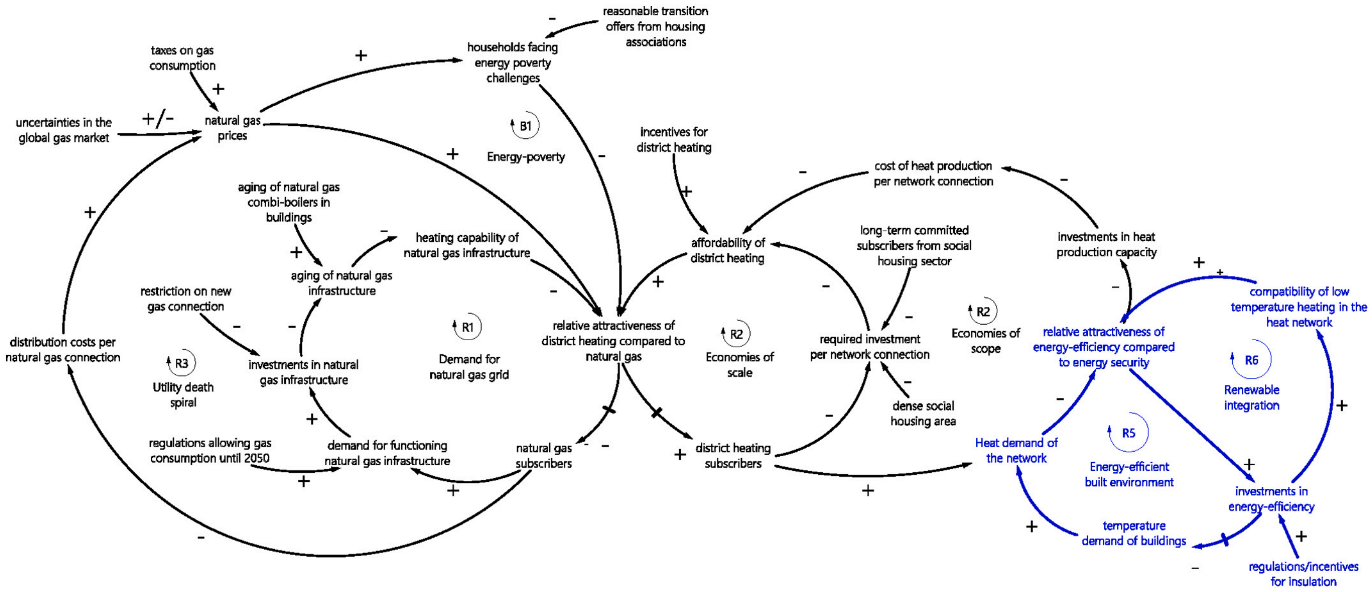

Fig. 8. The second phase of the transition plan: low carbon heating.

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

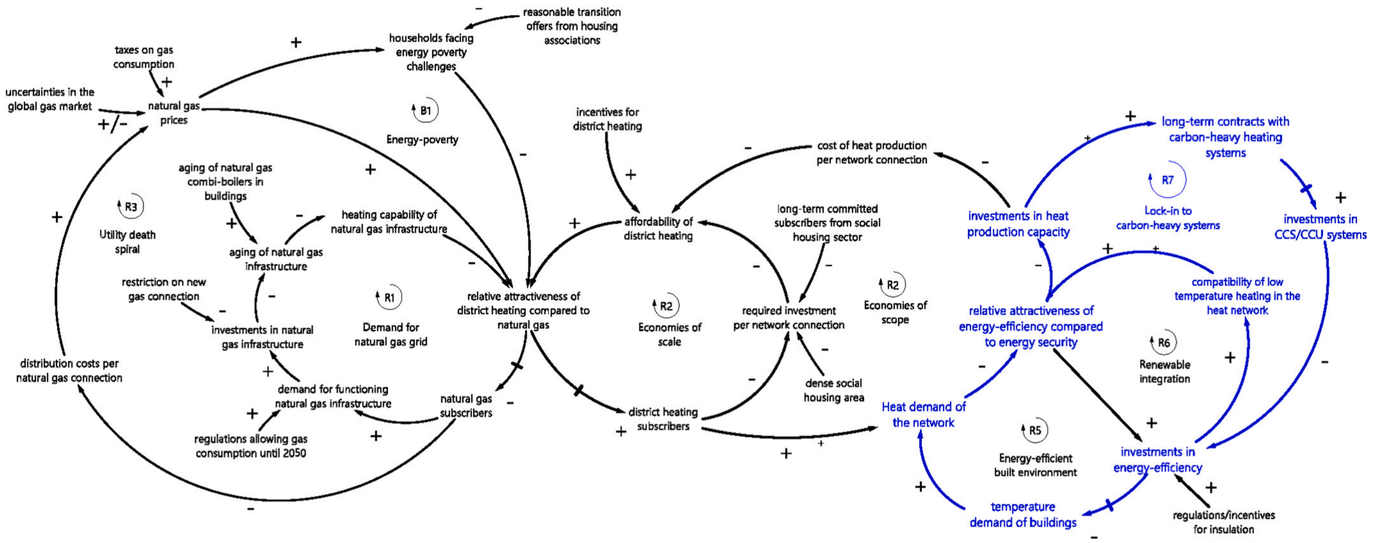

Fig. 9. A systemic trap during the no-regret transition: dependency on carbon-heavy systems.

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

5. 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. Fig. 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.

5.1. *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

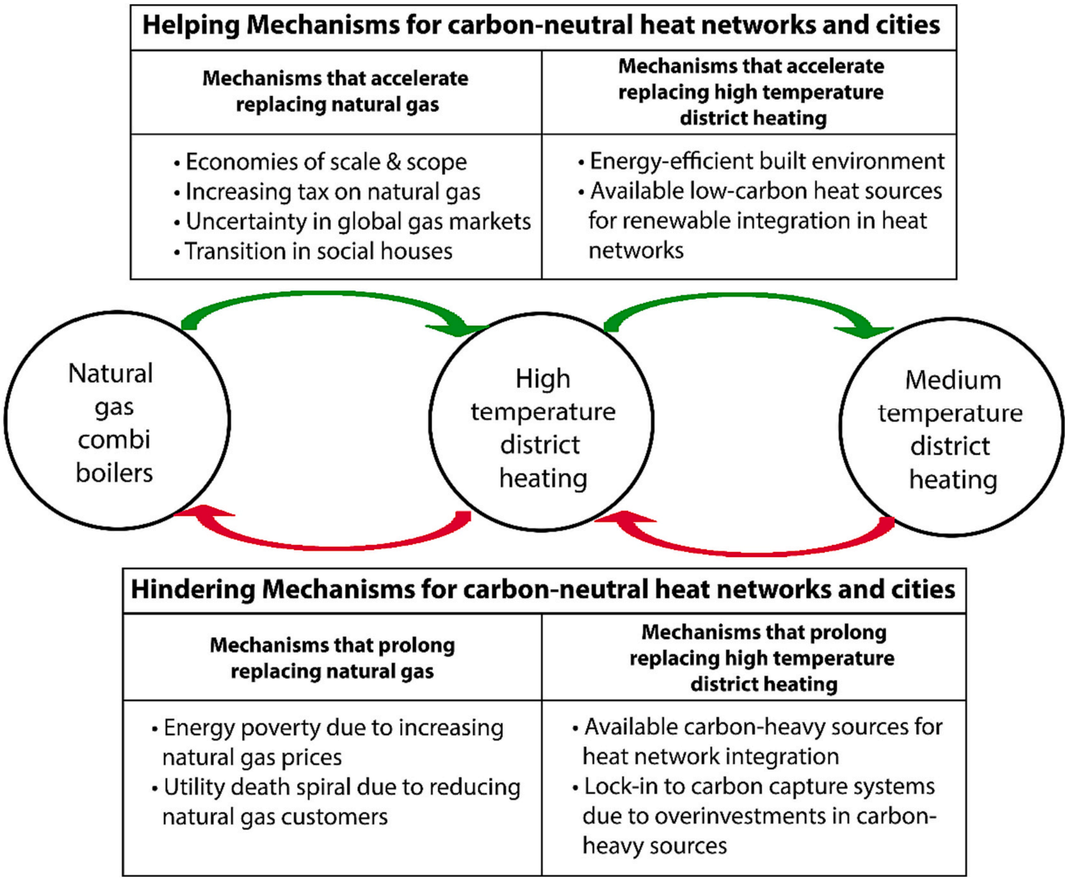

Fig. 10. Helping and hindering mechanisms for achieving carbon neutral cities with district heating systems.

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 modeling 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].

5.2. *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.

5.3. 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.

6. 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 policymakers 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.

Ethical statement

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

CRediT authorship contribution statement

C. Gürsan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **V. de Gooyert:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **M. de Bruijne:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **J. Raaijmakers:** Data curation.

Declaration of competing interest

Cem Gursan reports financial support was provided by Next Generation Infrastructure. Institute for Management Research, Radboud University, Houtlaan 4, 6525 XZ Nijmegen, the Netherlands reports financial support was provided by TKI Delta Technologie. Cem Gursan reports a relationship with Next Generation Infrastructure that includes: funding grants. Cem Gursan is a PhD candidate for the INSpECT project: INfrastructure interdependencies in Sustainable and inclusivE CiTies. Next Generation Infrastructure and TKI Delta Technologie has contributed to the funding of the PhD project. The funding code for the project is NGI-18002-2019-DT. More information about the research project and funders can be found at https://www.nginfra.nl/onderzoeken/inspect/.

Data availability

The parts of raw data and the processes data required to reproduce the above findings are available to download from https://data.mendeley.com/datasets/f8nwdjvhpf/4. The parts of raw data (interview and workshop transcripts) required to reproduce the above findings cannot be shared at this time in order to protect the anonymity of research participants due to ethical reasons.

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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:https://data.mendeley.com/datasets/f8nwdjvhpf/4.

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