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

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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.

1. Introduction

Today, cities accommodate approximately 55 % of the global population whereas they account for >60 % of global energy use and 70 % of emissions (C40, 2019; Seto et al., 2014). The UN expects that the urban population will reach 68 % by 2050 (UN, 2018). 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 (Nevens et al., 2013).

Infrastructure interdependencies have significant implications for both enabling or restricting the urban climate mitigation but remain understudied (Loorbach et al., 2010). 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 (Cass et al., 2018). Recognizing infrastructure interdependencies helps identifying patterns that can facilitate change in urban infrastructure systems, avoiding unexpected consequences, and overcoming

Abbreviations: ATES, Aquifer thermal energy storage; CO_2, Carbon dioxide; ECW, Expertise Centrum Warmte (Heat Expertise Center); ICT, Information and Communication Technologies; IEA, International Energy Agency; ISPT, Institute for Sustainable Process Technology; IPHE, International Partnership for Hydrogen and Fuel Cells; MLP, Multi-level perspective; NGinfra, Next Generation Infrastructures knowledge consortium; NVDE, Nederlandse Vereniging Duurzame Energie (Dutch Renewable Energy Association); PV, Photovoltaic; R&D, Research and development; RVO, Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency); SDE++, Stimulering Duurzame Energieproductie en Klimaattransitie (Stimulating Sustainable Energy Production and Climate Transition); SNG, Synthetic natural gas; UKCRIC, United Kingdom Collaboratorium for Research on Infrastructure and Cities; VPP, Virtual Power Plant; V2G, Vehicle to Grid.

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system lock-ins (Loorbach et al., 2010).

Although infrastructure interdependencies were highlighted previously (Cass et al., 2018), 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 (Loorbach et al., 2010). 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 (Nevens et al., 2013). 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?

2. Theoretical background

2.1. Infrastructures as socio-technical systems

Infrastructure systems refer to socio-technical systems (Geels, 2002) that produce, process, and distribute specialized services, materials, and assets (Loorbach et al., 2010) 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 (Sundnes, 2014). 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 (Bolton & Foxon, 2015). Societal institutions shape infrastructure systems by policies, lobbying, building coalitions, and forming the foundations for social norms, customs, and culture (Veeneman et al., 2009). Infrastructure systems shape institutions to recognize and satisfy societal needs through their functions (Jackson, 2010). Therefore, institutions and infrastructure systems co-evolve over time by addressing and shaping societal needs (Foxon, 2011). Looking from a transition governance perspective, the multi-level perspective framework (MLP) (Geels, 2002) 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 (Geels & Schot, 2007). 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 (Gürsan & de Gooyert, 2020). 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 (Rip et al., 1998). That said, the same stability indicates an inertia which might lead to barriers to fundamental changes in societal configurations (i.e. urban mitigation) (Loorbach et al., 2010). Incremental changes might not suffice to achieve climate goals, whereas fundamental changes can be resisted by the existing socio-technical configuration (Loorbach et al., 2017). Thus, a successful urban mitigation requires an understanding of how infrastructure systems are reconfigured.

2.2. Reconfiguration of infrastructure systems

Infrastructure systems evolve path-dependently (Cass et al., 2018). 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* (Rip et al., 1998). A technological trajectory can be defined as "the direction [in] which the technological paradigm advances" (Gürsan & de Gooyert, 2020, p. 15). Trajectories are influenced by interactions between socio-technical dimensions such as technological evolutions, policies and legislation, market and user preferences (Unruh, 2000). 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 (Meadows et al., 1974). Stakeholders try to materialize changes on infrastructure systems that they believe are beneficial according to their mental models (Frantzeskaki & Loorbach, 2010). 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 (Cass et al., 2018) through exploring the influential interactions between infrastructure systems (Frantzeskaki & Loorbach, 2010; Rogers et al., 2022) 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 (Unruh, 2000) which infrastructure systems need to develop incremental and evolutionary advantages (Rip et al., 1998). Incremental changes take place to prevent destabilization of infrastructure systems which could negatively affect urban services (Cass et al., 2018). Incremental reconfiguration implies that infrastructure services are gradually improved, provided affordably, efficiently, and without interruption (Raven & Geels, 2010). However, incremental reconfiguration may also signal a path-dependent inertia which could lead to lock-ins (Unruh, 2000). Lock-in can be defined as a rigid socio-technical trajectory that favors dominant systems and crowds out other emerging systems (Seto et al., 2016). Crowd out can be understood as the obstruction of investments to a desired technology due to the attractiveness of another technology (Gürsan & de Gooyert, 2020). Rigid trajectories, if under pressure from the landscape, can lead to the dealignment and radical reconfiguration of a system (Geels & Schot, 2007) which would hinder the continuity of infrastructure services.

With some exceptions (Rogers et al., 2022), 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 (Grafius et al., 2020), de-risking decisions and investments by avoiding unexpected consequences, and broadening the scope of cross-sectoral value generation in cities (Rogers et al., 2012). 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 (Cass et al., 2018).

2.3. Infrastructure interdependencies

In one of the earlier frameworks, Rinaldi et al. (2001) 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 (Zhang & Peeta, 2011). Spatial interdependency refers to the geographical proximity and collocation of infrastructure systems, such as physical sharing of networks, infrastructure components, and space (Carhart & Rosenberg, 2016). 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 (Dudenhoeffer et al., 2006), economic/budgetary, and market interdependencies (Friesz et al., 2007).

The advantages of considering infrastructure interdependencies are 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 (Monstadt & Coutard, 2019). 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 (Carhart & Rosenberg, 2015, 2016; Grafius et al., 2020; Raven & Verbong, 2007), mathematical papers on how to model and simulate infrastructure interdependencies without a deeper connection to socio-technical dimensions in cities (Li et al., 2019; Mohebbi et al., 2020; Prouty et al., 2020; Yang et al., 2019; Zhang & Peeta, 2011), or explorative papers on the resilience of critical interdependent infrastructure systems against landscape disruptions (Kang et al., 2017; Labaka et al., 2016; Marana et al., 2019; Monstadt & Schmidt, 2019). 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 (Leach & Rogers, 2020). 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 (Leach & Rogers, 2020). This would call for synthesizing the disciplinary knowledge that engineers have generated with a transdisciplinary lens (Rogers & Hunt, 2019). 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 (Bergek et al., 2015).

There have been some studies that explored infrastructure interdependencies in urban sustainability transitions from a socio-technical standpoint (Carhart & Rosenberg, 2016; Grafius et al., 2020; Leach et al., 2019; Rogers et al., 2012, 2022). To understand infrastructure interdependencies, it is important to note that infrastructure systems are structurally coupled with their socio-technical context (Bergek et al., 2015). In other words, the context influences infrastructure systems and infrastructure systems influence their context. Interdependencies often cross system or sector boundaries (Nevens et al., 2013). Notably, UKCRIC has applied systems mapping to understand developments in the built environment and infrastructure systems in the United Kingdom (Rogers et al., 2022). 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 Fig. 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.

3. 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 (Janz & Muethel, 2014). 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 (Niknazar & Bourgault, 2017). Finally, we bring together

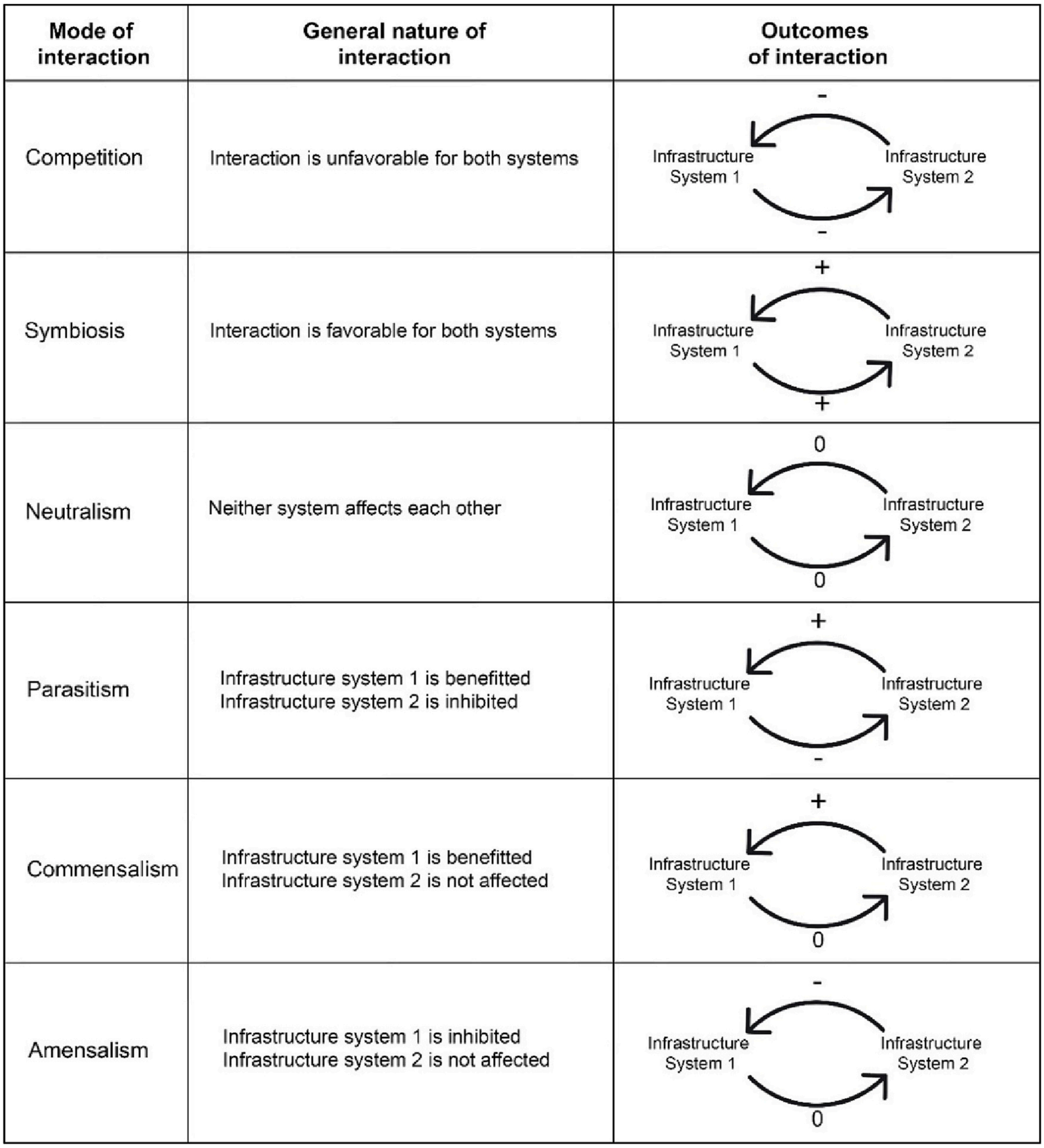


Fig. 1. Multi-mode relationship framework (adapted from Sandén & Hillman, 2011).

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.

3.1. 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 (World Bank, 2020). 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 (Dutch Parliament, 2019). 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 (IEA, 2020). Thus, it is safe to assume that we can encounter relevant recent examples of infrastructure systems and their interdependencies by investigating the Netherlands.

3.2. 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 (Cass et al., 2018) and the potential reconfigurations in the system structures

(Gürsan & de Gooyert, 2020). 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 (Dutch Parliament, 2019). 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 (Janz & Muethel, 2014). For this paper, we conducted 10 semi-structured interviews. The initial set of interviewees was 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 and 70 min. More information on the research participants and their contributions can be found in the Appendix B and attached data folder.

3.3. 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 (Schadewitz & Jachna, 2007). We use the multi-mode relationship framework (Pistorius & Utterback, 1997; Sandén & Hillman, 2011) to identify interactions between infrastructure systems. The multi-mode framework provides a rich setting for discussing interactions amongst systems due to high interconnectivity (Gürsan & de Gooyert, 2020). We synthesize and build on a range of infrastructure interdependency frameworks (Carhart & Rosenberg, 2016; Dudenhoeffer et al., 2006; Friesz et al., 2007; Grafius et al., 2020; Kang et al., 2017; Raven & Verbong, 2007; Rinaldi et al., 2001; Zhang & Peeta, 2011). 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 Fig. 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.

4. 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.

4.1. Functional interdependency

Functional interdependencies occur when interconnected infrastructure systems have complementary or competing functions which influence the functionality of both systems (Zhang & Peeta, 2011). 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 (Schepers & Van Valkengoed, 2009).

To illustrate a symbiosis example, in the Merwede project (Utrecht Municipality, 2020), 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 reveals 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 (IEA, 2020), 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 (IEA, 2020). Heat pumps, on the other hand, have attracted an interest as an efficient alternative heating system in the Netherlands (Schumacher, 2021) 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 (Dutch Parliament, 2019). 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

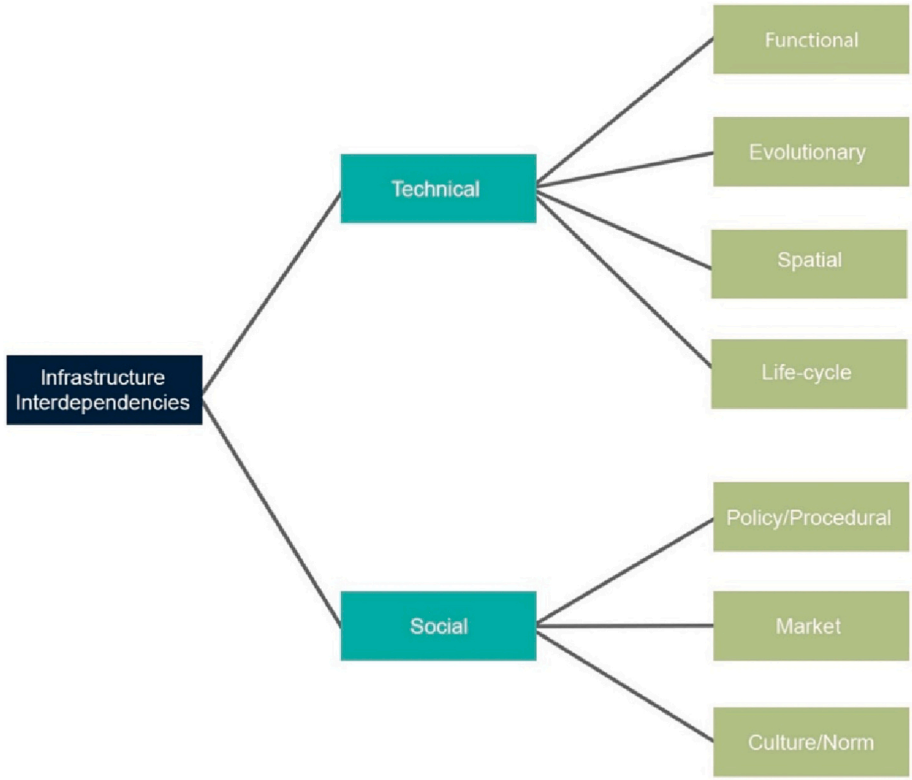


Fig. 2. Infrastructure interdependency types coding tree.

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.

4.2. 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 (Rip et al., 1998). Evolutionary characteristics of infrastructure systems consist of technical roots of technologies, accumulated R&D (Rip et al., 1998), problem solvers that define "relevant" problems (Dosi, 1982), users and markets that influences the boundary of "relevance" with their choices (Geels, 2002), and policies and governance structures that influence the infrastructure systems and their markets (Unruh, 2000). 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 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 (Dutch Parliament, 2019) 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

[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													Mobility			
									individual					central											
	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)	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, 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	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, 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	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)	FCP, PCP	FCP, PCP		FP	FS	FS	FS, ES	FS	FS, ES	FS, ES	FS	FS	FP	FS	FS, ES, SS	PCP	PCP	PCP	FS	FS, PCP	FS	ES	ECM, FS	ECM, FS	ECM
Natural Gas (Electricity)	FP, MCP	FP, MCP	FP		FS	FS	FS, ES	FS	ES, SS, CNS	ES, SS, CNS	FS, ES	FS	ES, SS	FCP, ECM	FP	ECM	ECM	ECM	FS, LS, LA	FP	FS	ECM	ECM	ECM, FS	ES
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	FS	FS	FS	FS	FS	FS	FS	FS	ECM	EB, FS	ES, PCP, FS, MS, CNCP	ECM
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	FS	FS	FS	FS	FS	FS	FS	NT	ECM, FS	ECM, ES, FS	FS, ES, MS, CNS, CNCP	ECM
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	FS	PCP	FS, FCP, PCP	FS, FCP, PCP	PCP	ECM	FS	ECM, FCP	ECM	ES, FS	ECM, ES, FS	ECM
Hydrogen Storage	FS	FS	FS	FS	FS	FS, ECM	FS, ES, MS		ES	ES, FS	FS	FS	FCP	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	PCP	PCP	FS, ES	ES, SS, CNS	FS	ES	FS, ES	ES		ES, SS	FS	FS	SS, FP	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	ES	ES	FS, ES	ES, SS, CNS	FS	FS, ECM	FS	ES, FS	ES, SS		FCP	FS	SS, FCP	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)	FS,MCP	FS,MCP	FS	FS, ES	FS	FS	FS	FS	FS	FCP		FS	FS	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, ES, SS	NT	FS	FS	FS	FS	FS	FS	FS	FS	FS		FS	FS	FS	FS	FS	FS	FS	ES	FS	ES	ES	ES	ECM
Natural Gas (Heating)	FP, MCP	FP, MCP	FP	ES, SS	FS	NT	FCP	FCP	SS, FP	SS, FCP	FS	FS		FS, FP	FP	FP	FP	FP	FS	FS	FS	ECM, FS	ECM, FS	ECM, FS	ES
Heat pumps (central)	FS	FS, MCP	FS	FCP, ECM	FS	FS	FS	FS	FS	PCP, FCP, SCP	ES, FS	FS	FS, FP		FCP,PCP	FS, ES, PCP	FS, ES, PCP	FS, PCP	FS	FS	FS	ECM	ECM	ES, MCP	ECM
Biomass plant	FCP, PCP, ECM	FCP, PCP, ECM	FS, ES, SS	FP	FS	FS	PCP	PCP, FCP	ES	PCP, FCP, SCP	FCP	FS	FP	FCP,PCP		PCP, FS, FCP	PCP, FS, FCP	PCP, FCP	FS	FS, FCP	FS	ES	ECM, FS	ECM, FS	ECM
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	FS, ES, PCP	PCP, FS, FCP		ES, FS, PCP	PCP, FCP	FS	FS	FS	ECM	ECM	ES	ECM
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	FS, ES, PCP	PCP, FS, FCP	ES, FS, PCP		PCP, FCP	FS	FS	FS	ECM	ECM	ES	ECM
Residual Heat	PCP	PCP	PCP	ECM	FS	FS	PCP	PCP, FCP	FCP, PCP, SCP	PCP, FCP, SCP	FS, FCP	FS	FP	FS, PCP	PCP, FCP	PCP, FCP	PCP, FCP		FS	FS	FS	NT	NT	NT	NT
District Heating	FS	FS	FS	FS, LS	FS	FS	ECM	FCP	FCP, PCP, SCP	SCP, FCP	FS, FCP	FS	FS	FS	FS	FS	FS	FS		FS	FS	NT	NT	NT	NT
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	FS	FS, FCP	FS	FS	FS	FS		FS	ECM	ECM	ES, FS	ECM
Seasonal Heat Storage	FS	FS	FS	FS	FS	NT	ECM, FCP	ECM, FCP	FCP	SCP, FCP	FS	FS	FS	FS	FS	FS	FS	FS	FS	FS		NT	NT	NT	NT
Biofuel	ECM	ECM	ES	ECM	ECM	ECM, FS	ECM	ECM	ES	ECM	ECM	ES	ECM, FS	ECM	ES	ECM	ECM	NT	NT	ECM	NT		FCP, FS, ECM, SS	FCP, FS, ECM	FP, ECM
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	ECM	ECM, FS	ECM	ECM	NT	NT	ECM	NT	FCP, FS, ECM, SS		FCP, ECM	FP, ECM
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	ES, MCP	ECM, FS	ES	ES	NT	NT	ES, FS	NT	FCP, FS, ECM	FCP, ECM		FP, ECM
Fossil Fuel	ECM, MCP	ECM, MCP	ECM	ES	ECM	ECM	ECM	ECM	ECM	ECM	ECM	ECM	ES	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
	Dutch example
	Literature example

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) (Dutch Parliament, 2019). 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 supply a high temperature water regime to its users (Rotterdam municipality, 2021). 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 (B. L. Schepers & van Lieshout, 2011) 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.

4.3. 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 (Knijp, 2019), 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 (Stedin, 2019). 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 (Dutch Parliament, 2019). Due to limited underground space in Dutch urban areas (Claassens et al., 2020), 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 (Niessink, 2015). In Rotterdam, the symbiosis between heating network and aquathermal would be much more stronger (Rotterdam municipality, 2021) 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.

4.4. Life-cycle/temporal interdependency

Life-cycle/Temporal interdependencies occur due to differences in technological life-cycle stages (Bolton & Foxon, 2015) and product lifespans (Murakami et al., 2010) as well as existing contracts for system use (Verweij & van Meerkerk, 2020). Effects of this interdependency type become more apparent due to the urban temporalities that influence a change on the socio-technical systems (Monstadt & Coutard, 2019), 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

[2] Transitioning system, in this section, means: a technology, fuel or system that can substitute carbon emitting systems in the short and medium term (Gürsan & de Gooyert, 2020). 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 (Gürsan & de Gooyert, 2020). For a transition technology example, using biomass to replace high temperature coal demand before carbon-neutral technologies emerge can be considered (Dutch Parliament, 2019).

sustainable emerging infrastructure systems by leading to *windows of opportunities* (Geels, 2002) and a "system renewal and transition" stage (Bolton & Foxon, 2015). 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 (Monstadt & Coutard, 2019).

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 (Gemeente Eindhoven, 2018) 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 (Gürsan & de Gooyert, 2020). If a vital infrastructure system is phased-out, its interdependent systems could suffer from losing their symbiotic functions. Furthermore, societal 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) (Niessink, 2015). 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 (Bitsch et al., 2012; Galonske et al., 2004). 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 (Heath & Read, 2014). 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.

4.5. 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 (Veeneman et al., 2009). Urban actors and institutions construct the selection mechanism that makes an urban value "relevant" which, in turn, affects how policy instruments are designed (Walker, 2000). 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 (de Gooyert et al., 2016). 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++ (RVO, 2021), 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 (ECW, 2021a). 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 (ECW, 2021b). 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 or own fossil fuel based heat sources which in turn creates substantial market entry barriers for emergent alternative low-carbon heating systems (Osman, 2017). District heating networks are attractive heating systems that can reach a large customer base with ease while ensuring profitability (Osman, 2017); 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 (Osman, 2017). 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 (RVO, 2021), 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.

4.6. 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 (Friesz et al., 2007). Changes in one of the energy and infrastructure service markets could essentially have indirect effects in other markets (Gürsan & de Gooyert, 2020). 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 (Heldeweg & Saintier, 2020). 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 (Gerritse, 2019), 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 (Dutch Parliament, 2019). On the end-user side, there will be new loads on the electricity grid due to electric-stoves, heat-pumps, and electric cars (Jones et al., 2018). 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 (Jones et al., 2018). 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 (Jones et al., 2018). As the flexible load becomes significantly large as in highly renewable systems, it is critical to maintain the symmetry between supply and demand (Pérez-arriaga & Battlle, 2012) and deploy price-responsive technologies (Rootzén et al., 2020) 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 (Yuan et al., 2021). 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.

4.7. *Culture/norm interdependency*

Service users create a symbolic meaning of infrastructure systems and services over time (Geels, 2002). 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 (Kivimaa et al., 2019). 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 (Gerritse, 2019). 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 (Mourshed et al., 2015). 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 (Gerritse, 2019). If nurtured well, these changes can be cultivated into a stewardship for the environment and ambition for energy autonomy amongst 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 amongst 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 happens during the daytime. Thus, there is a time lag between peak demands and intermittent electricity production. In the CityZen project (Gerritse, 2019), 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.

5. Discussion

Except for a few studies (Grafius et al., 2020; Rogers et al., 2022), 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.

5.1. 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.) (Monstadt & Coutard, 2019). Urban transitions emerge not in isolated individual domains but as a result of co-evolutions within the “fabric of the urban space” (Monstadt & Coutard, 2019, p. 2193). Therefore, the urban system cannot be understood independently from their historical, geospatial, technical and socio-political context (Basu et al., 2019). 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 (Stein et al., 2014). 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 (Monstadt & Schmidt, 2019). Therefore, these cognitive challenges and institutional restrictions hinder the ability for organizing cross-cutting co-management and robust decision-making in urban infrastructure transitions (Monstadt & Coutard, 2019; Unruh, 2000). 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 (Angheloiu & Tennant, 2020) (ii) and consider the effects of interconnections, higher order effects, and links across the system boundary (Lovins & Lovins, 2001) over a range of socio-technical dimensions (i.e. policies, markets, technologies, etc.) (Geels, 2002), scales (i.e. government, municipal, households) (Castán Broto & Sudhira, 2019), and urban temporalities (Monstadt & Coutard, 2019).

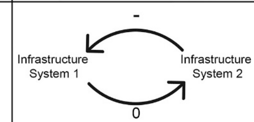
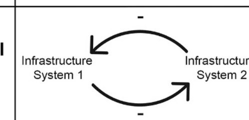
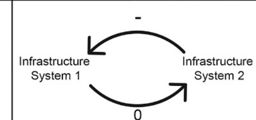
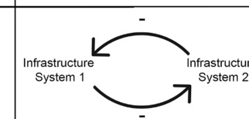
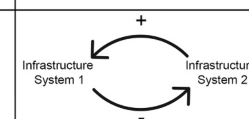
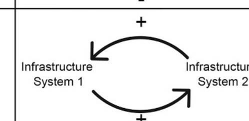
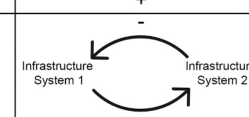
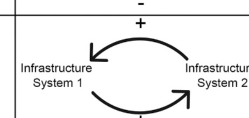
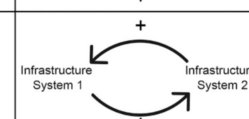
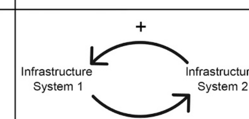
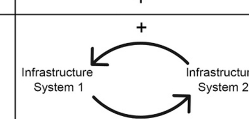
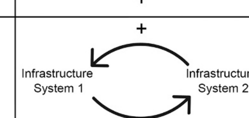
Overall, cities are densely populated compact spaces, a system of systems, where different infrastructure sectors and urban services simultaneously collaborate and compete to ensure the continuity and quality of urban life (Bulkeley & Castán Broto, 2013). The interconnections in socio-technical systems can easily transcend the system and sector boundaries in cities (Nevens et al., 2013). 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 (Frantzeskaki & Rok, 2018). 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.

5.2. 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 (Dudenhoeffer et al., 2006), Market (Friesz et al., 2007), and Culture/Norm (referred as “Societal”) (Dudenhoeffer et al., 2006) by using socio-technical dimensions in the MLP framework (Geels & Schot, 2007). 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 (Heldeweg & Saintier, 2020). 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 (Gerritse, 2019). 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 (Carhart & Rosenberg, 2015) and evolutionary interdependencies. Identifying and understanding time-dependent interdependencies calls for a dynamic analysis, an analysis of how the system can change over time (Gürsan & de Gooyert, 2020). 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 (Bolton & Foxon, 2015). 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 (Bergek et al., 2015). 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.

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	
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	
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	
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	
Lock-in	Prolonged consumption of fossil fuels in bundled systems can crowd-out alternative heating systems	Life-cycle parasitism	
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	
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	
Influencing user behavior	Interfaces in smart-grids changes the social routines and habits for energy consumption.	Culture/Norm symbiosis	
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	
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	
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	
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	

5.3. 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 (Frantzeskaki et al., 2012). We argue that applying the proposed interdependency framework within multi-stakeholder engagement spaces (Frantzeskaki & Rok, 2018) could identify new opportunities to utilize interdependencies in urban transitions (i.e. by using urban transition labs (Nevens et al., 2013), transition scenarios (Frantzeskaki et al., 2012) or group model building (Andersen et al., 2007). 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.

6. 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 (Carhart & Rosenberg, 2015) 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.

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Ethical statement

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

CRediT authorship contribution statement

C. Gürsan: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization. **V. de Gooyert:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition, Project administration. **M. de Bruijne:** Conceptualization, Methodology, Writing – review & editing, Supervision. **E. Rouwette:** Conceptualization, Methodology.

Declaration of competing interest

Next Generation Infrastructures and TKI Delta Technologie.

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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 address and link:

Gürsan, Cem; de Gooyert, Vincent (2023), "Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent

insights from the Netherlands", Mendeley Data, V6, doi: 10.17632/r95hxbfvb8.6
https://data.mendeley.com/datasets/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) Fig. 1, In JPG and PDF format.
9) Fig. 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
Reviewed documents for the case study.

Name	Reviewed document	Description of the reviewed document	Organization	Date	Type of document	Reviewed 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 MERWEDE	Urban plan for redeveloping the Merwede as an integrated residential neighborhood.	Utrecht Municipality	6-Nov-20	Urban plan	186

Table 4
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*

(continued on next page)

Table 4 (*continued*)

Responsibility	*Organization type*	*Contributed information*
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?*

Table 5
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

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 are the current infrastructure system influence other infrastructure systems due to its functions (e.g. material input-output, supply-demand, informational input-outputs, etc.)? How are 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 would 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 (Gürsan & de Gooyert, 2020)?
  o 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? (Rogge & Reichardt, 2016)
- 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?
  - o 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)
- Do we included 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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