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On accelerating the development of configurational innovation systems—the case of non-urban district heating in Germany

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ABSTRACT
The decarbonizing the heat sector is a major challenge in the energy transition in Germany and elsewhere. District heating systems could play an important role in this context. However, the diffusion of the technology in Germany has been very slow. The paper presents a comprehensive analysis of the technological innovation system (TIS) to enhance understandings of the impediments to the diffusion of non-urban district heating systems. Due to its strong local context dependence, district heating can be understood as a configurational technology, and the TIS in which it is embedded as a configurational TIS. The paper contributes to the literature by developing policy suggestions that could lead to an acceleration of the diffusion of locally context-dependent technologies. The author recommends that policymaking in configurational TIS should aim at designing smart innovation system structures that can manage a high level of context specificity and facilitate vertical and horizontal knowledge exchange.

KEYWORDS
Technological innovation systems; configurational innovation systems; district heating; Germany; heating transition

1. Introduction

While Germany has been praised for its rapid transition to a renewable electricity system, the low-carbon transition of its heat sector is still very slow. In order to reach its reduction targets for greenhouse gas emissions, the German government has pledged to decrease the carbon emissions from its building stock substantially (BMWI, 2010, 22). One option to contribute to reducing carbon emissions in the heat sector is the widespread deployment of district heating systems that use low-carbon sources such as renewable sources (Blömer et al. 2017), especially in non-urban settings[1] where diffusion has been low. To date, there has been a lack of studies of the reasons for this slow development. This paper aims to contribute to filling this gap in two ways. First, we aim to provide a better empirical understanding of the influencing factors. We conducted an analysis of the non-urban district heating technological innovation system (TIS). This was based on interviews with actors who participated in implementing a new district heating system, and interviews with national-level experts in Germany. The TIS framework assumes that technologies are embedded in systems that influence their diffusion (Carlsson and Stankiewicz 1991). Recently, the literature has started to acknowledge that TIS can have different characteristics and development patterns (Binz and Truffer 2017). These include the technology's level of local context dependency (Wesche et al. 2019). Wesche et al. (2019) coined the term "configurational innovation systems" as a subtype of technological innovation systems. Configurational innovation systems evolve around technologies that are strongly dependent on their local context and need to be configured with regard to specific local contingencies.

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[1]We define non-urban district heating settings as projects that are implemented in settlements with fewer than 10,000 inhabitants.

The counterpart of configurational innovation systems are generic innovation systems. These evolve around technologies that are largely independent of the local context in their implementation. Since the concept of configurational TIS is nascent, it is not yet clear how policymaking can accelerate the development of configurational TIS.

The second aim of this paper is to contribute to a better understanding of how policies need to be formulated in order to advance configurational TIS. Based on the empirical analysis, we make policy recommendations for how to accelerate the diffusion of non-urban district heating systems.

2. Analyzing and designing policy for configurational innovation systems

The theory section is divided into three parts. The first part gives a short introduction to TIS. The second presents the specificities of the configurational innovation system and its counterpart, the generic innovation system. The third outlines how policymaking in configurational innovation systems needs to reflect the local context dependence.

2.1. Technological innovation systems

The development and diffusion of (technological) innovations takes place in socio-technical systems, which are at the core of the TIS (Carlsson and Stankiewicz 1991; Markard and Truffer 2008b). The key idea is that innovations do not develop in a vacuum but are embedded in socio-technical structures that influence their development and diffusion. These structures can be classified as three types: actors and their interaction, rules and institutions, and infrastructures. Actors are differentiated into several categories, including individuals, organizations, and networks, which interact with each other (Wieczorek and Hekkert 2012, 76). Rules and institutions include "hard" institutions such as legislation, standards or other codified rules, and "soft" institutions, which encompass norms and values, and as well as a "set of common habits, routines and shared concepts used by humans in repetitive situations" (Wieczorek and Hekkert 2012, 76). Infrastructure is understood as "the basic physical and organizational structure needed for the operation of a society or enterprise or the services and facilities necessary for an economy to function" (Negro, Alkemade, and Hekkert 2012, 3838) and includes knowledge infrastructure, physical infrastructure, and financial infrastructure (Wieczorek and Hekkert 2012, 77).

When networks of actors engage in activities that contribute to the development and diffusion of innovations, an innovation system will start to develop. The key processes that evolve in the development process of innovation systems are called functions. Several sets of functions have been suggested (Bergek et al. 2008; Hekkert et al., 2007b). In our study, we used the set of seven functions proposed by Hekkert et al 2007b, as also used by Wesche et al. (2019): (1) experimentation and production by entrepreneurs, (2) knowledge development, (3) knowledge exchange, (4) guidance of search, (5) market formation, (6) resource mobilization, and (7) creation of legitimation (7) (see Table 1).

Systemic problems are problematic elements in the system structure that inhibit an innovation system from functioning well (Negro, Alkemade, and Hekkert 2012; Wieczorek and Hekkert 2012). Policy measures can influence the system in such a way that system functioning is improved.

The TIS framework has been applied in many empirical studies (Dewald and Truffer 2012; Markard and Truffer 2008a; Negro, Hekkert, and Smits 2007). Recently, increasingly more authors have acknowledged that it is useful to distinguish between types of TIS that are very different in character. TIS have been differentiated with respect to the structure of the value chain within a TIS (Stephan et al. 2017), the mode of valuation (Huenteler et al. 2016), the geographic "scalarity" (Binz and Truffer 2017), the mode of innovation and knowledge generation (Binz and Truffer 2017), and the level of local context dependence (Wesche et al. 2019).

Table 1. Description of seven key system functions (Reichardt et al. 2016, 12, which is based on Hekkert et al.,2007b).

Function number	Function name	Description
F1	Experimentation and production by entrepreneurs	Entrepreneurs are essential for a well-functioning innovation system. Their role is to turn the potential of new knowledge, networks, and markets into concrete actions to generate new business opportunities and take advantage of them.
F2	Knowledge development	Mechanisms of learning are at the heart of any innovation process, where knowledge is a fundamental resource. Therefore, knowledge development is a crucial part of innovation systems.
F3	Knowledge exchange	The exchange of relevant knowledge between actors in the system is essential to foster learning processes.
F4	Guidance of search	The processes that lead to a clear development goal for the new technology based on technological expectations, articulated user demand, and societal discourse all enable selection, which guides the distribution of resources.
F5	Market formation	The function refers to the creation of a market for the new technology. In early phases of developments this can be a small niche market, but later on a larger market is required to facilitate cost reductions and incentives for entrepreneurs to move into that market.
F6	Resource mobilization	Financial, human and physical resources are necessary basic inputs for all activities in the innovation system. Without these resources, other processes will be hampered.
F7	Creation of legitimation	Innovation is by definition uncertain. A certain level of legitimacy is required for actors to, for example, commit to the new technology and execute investments, and make adoption decisions.

2.2. Configurational innovation systems

Wesche et al. (2019) suggest that some TIS are more influenced by the local context than others. They introduced two archetypes of TIS: the generic innovation system, and the configurational innovation system. Generic innovation systems encompass what Fleck (1993) calls generic technologies. Such technologies are not very context-dependent and can easily be mass-produced; they can be used in or added to existing structures. Examples of generic technologies are electric cars (Wesseling et al. 2014), solar panels (Dewald and Truffer 2011) and wind turbines (Johnson and Jacobsson 2003; Reichardt et al. 2016). By contrast, configurational innovation systems encompass what Fleck (1993) referred to as configurational technologies. Such technologies are strongly dependent on the local context and the available structures. Thus, they always need to be configured according to local contingencies, which decreases their potential for rapid diffusion.

In their analysis, Wesche et al (2019, 110) emphasize that the "generic or configurational nature of the focal technology has a major effect on the structure and functions of the innovation system supporting it." For example, while generic technologies can develop dominant designs rather quickly, it is rather difficult for configuration technologies to achieve the same, which leads to the continuous need for experimentation, and fewer resources can be channeled into upscaling a limited number of solutions. Furthermore, while knowledge development in generic innovation systems is in the hands of a smaller group of upstream actors, in configurational innovation systems, "a large share of knowledge development and learning takes place not only upstream but also at the point of deployment" (Wesche et al. 2019, 110), which results in a larger number of people needing to act. This larger number of actors operating in dispersed fields of the innovation system complicates knowledge diffusion and hinders the emergence of a clear guidance of the search.

When differentiating between generic and configurational TIS, it is helpful to think of them as two poles of the same dimension (see Fig. 7 in Wesche et al. 2019, 110). No TIS is completely generic or completely configurational. For example, a wind turbine TIS can be categorized as a generic TIS, but that does not exclude that the diffusion of wind turbines is also influenced by local contingencies such as local spatial planning or the availability of an electricity grid.

2.3. Propositions for theoretical advancement

We suggest that the differentiation between the two types of generic innovation systems and configurational innovation systems leads to a general repercussion for TIS-based policymaking. Specifically, we suggest that policymaking in configurational innovation systems needs to resonate with stronger local context dependence.

National or European policies are generic by definition. However, their design can enable them to address local contingencies to a greater or lesser extent. For example, in the 1990s and 2000s, feed-in-tariffs were able to propel the generic renewable electricity TIS in Germany forward (Wesche et al. 2019). The incentive structure of the policies enabled the generic technologies for renewable energy generation to develop dominant designs much faster, to be produced in series, and to be deployed at scale in a short period of time. By contrast, due to a higher diversity of local contexts, configurational innovations are likely to be faced with a substantially larger number of context-related systemic problems, which would lead to higher system fragmentation. Thus, policies need to encompass more than just incentive-based instruments and they need to entail a comprehensive yet diverse set of specific policy instruments in order to create smart innovation system structures that enable local actors to cope with the high level of context specificity. Thus, our approach follows recommendations, for example by Rosenow, Kern, and Rogge (2017), that policy mixes need to be well-targeted and comprehensive.

3. District heating as a configurational innovation system

In this section we give a brief overview of non-urban district heating in Germany in order to provide a better understanding of the scope of TIS and to show that a TIS is a configurational TIS.

The German government intends to decrease substantially the carbon emissions from its building stock (Bundesministerium für Wirtschaft und Energie 2010, 22). While there are many potential strategies to decarbonize the heat supply (Britton et al. 2021), one promising strategy instrument is district heating systems using low-carbon sources such as renewable sources and waste heat sources (BMUB, 2016, 41; Bareiß 2020). In 2016, less than 15% of German households were supplied by district heating systems (Bundesverband der Energie- und Wasserwirtschaft, 2017, 8). This is a very low percentage compared with, for example, in Demark and Austria, where the shares were respectively ca. 63% in 2015 (Danish Energy Agency 2015, 4) and 26% in 2017 (Fachverband Gas Wärme 2018, 21). The general advantage of district heating is that heat production takes place more efficiently compared with heating solutions for individual buildings. The efficiency gains are generated by higher economies of scale (Lund et al. 2014, 1), which can lead to fewer greenhouse gas emissions. Furthermore, even more CO_2 emissions can be avoided if the heat sources are carbon neutral.

As of 2017, 1454 district heating networks were installed in Germany (Euroheat and Power 2019). Most of these existing district heating systems in Germany are located within larger cities, and therefore most new district heating systems need to be installed in smaller cities or rural environments (Jochum et al., 2017). While research has shown substantial economic potential for new district heating systems (Blömer et al. 2017; Jochum et al.), the number of district heating systems only grew slowly during the last decade: just over 100 new district heating systems were installed between 2011 and 2017 (Euroheat and Power 2019).

The non-urban district heating TIS is configurational in character, as district heating systems cannot be produced in series, and they are largely contingent upon the local context. Each new project needs to be specifically designed to fit with the local contingencies, which include the current state of heating infrastructure in the target area, the availability of a heat supply (e.g., waste heat, biomass), the building structure (existing buildings or new buildings), the local population's willingness to connect to a district heating system, local political support, and the local topography. Since district heating projects are complex configurational projects, the implementation of each project will be unique to some extent.

4. Methods

As technology implementation in configurational TIS takes place in a variety of local contexts, it is necessary to use data collection methods that capture specifically the local contingencies. Otherwise, conclusions are likely to miss relevant issues. For this reason, we chose a two-tiered approach in our study.

First, we conducted 20 interviews with 20 actors who had initiated or substantially supported the successful implementation of four low-carbon district heating systems, namely project developers, company and industry representatives, local and regional politicians, and representatives of utilities and communities. We chose to focus on successfully implemented projects because they had passed through the whole implementation process and involved actors, and therefore might give insights into more elements of the TIS than actors involved in unsuccessful projects. Since data on heat grids in Germany are dispersed and fragmented, and the data from Euroheat & Power are of low level of detail, we screened several German databases for district heating projects in order to be able to identify important archetypes. The screening process led to a list of more than 100 heat grids. Many of the heat grids currently operating are in German cities. The main challenge for these grids is to switch their heat supply from fossil fuels to renewable fuels as quickly as possible. By contrast, new heat grids are more likely to be implemented in non-urban settings, which is the focus of this paper. To compare different archetypes of non-urban heat grids, we chose four district heating systems with contrasting characteristics. The selected four projects differed according to their settlement structure, temperature levels in the grid, type of heat source, and the institutional background of the grid operator (see Table 2 for an overview).

Second, we conducted nine interviews with nine national-level experts, whom we asked questions about the non-urban, district heating innovation system as a whole. The nine interviewees worked in the German heating sector (cf. Table 3). They were selected due to their knowledge of the scope of TIS and because they were known for their expertise.

All interviews were conducted in spring and summer 2016, and they were carried out as semi-structured interviews. Following an introduction to the aim of the study and data protection issues, the national-level actors were asked questions that focused on the national level and their experiences in other district heating system related projects. The project-related interviewees were first asked about the project implementation process, then about factors that influenced the emergence of the district heating systems, and finally for their recommendations for how to accelerate the diffusion of non-urban district heating systems. All interviews were recorded, transcribed, and coded with respect to the seven functions listed in Table 1. The interviews were coded independently by the first author and a research assistant. Differences in the coding results were analyzed and in cases where classifications differed, ambiguous categories were refined, and non-fitting codes were eliminated.

5. Innovation system analysis

The first part of our analysis describes the structure of the non-urban, low-carbon district heating innovation system (hereafter referred to as the district heating innovation system). We then analyze the key processes and systemic problems throughout four development stages of the analyzed non-urban district heating projects. In the last part of the analysis, the paper displays the performance of the district heating innovation system's functions.

5.1. Structural elements of the German district heating tis

The following overview is mainly based on the interviews. Information that is not based on the interviews is supported by published literature.

Table 2. Overview of four non-urban district heating systems and project-related interviewees.

	Supplied buildings	Grid length	Heat generation technology	Operator	Type of buildings	Interviewees
Project A	ca. 270	15.5 km	Waste heat, wood chips	Regional operator	Existingneighborhood	Mayor (ID #1), CEO of project developer (ID #2), project manager of project developer (ID #3), leader of local environmental group (ID #4), CEO of local waste heat supply company (ID #5), former head of local energy agency (ID #6), CEO of local heating oil supply company (ID #7)
Project B	ca. 25	1 km	Near-surface geothermal energy, heat pumps	Municipality	Newly built neighborhood	Local civil servant and co-initiator (ID #8), CEO of local renewable energy company and co-initiator (ID #9), mayor (ID #10), former mayor (ID #11), CEO of tech provider and project developer (ID #12), researcher at a regional technical college (ID #13), manager in a national utility company involved in the project (ID 14)
Project C	ca. 190	6 km	Biogas, biomass	Local energy	cooperative	Existing neighborhood
Mayor and co-			initiator CEO of local agri-enterprise and co-initiator (ID #15), member of executive board of local energy cooperative and co-initiator (ID #16), mayor (ID #17)			
Project D	47	1.8 km	Solar thermal, heat pumps, solar PV, natural gas	Municipality-owned enterprise	Existing neighborhood	Mayor (ID #18), CEO of local heat technology enterprise and co-initiator (ID #19), CEO of local software enterprise and co-initiator (ID #20)

Table 3. Overview of the nine national-level expert interviewees.

ID	Position	ID	Position	ID	Position
#21	Energy researcher	**#24**	Representative of a heat technology think tank	**#27**	Manager in an integrated heat technology incumbent
#22	Representative of a heat tech association	**#25**	Representative of a fossil fuel heat tech campaigning group	**#28**	Heating-related project manager of a state-level energy agency
#23	Representative of a renewable energy association	**#26**	Representative of the national chimney sweepers association	**#29**	Manager in a pipe tech company

5.1.1. Actors

Non-urban district heating projects are often launched by local project initiators, who are often lay people and seldom trained in any field of expertise relevant to district heating. Consequently, during the implementation process of the projects such lay people often require support from project planning and development companies, and from knowledge intermediaries. A number of other actors need to contribute in order for projects to be implemented at the local level. For example, supplier companies are needed to provide technological components, banks and investors are needed to provide loans and capital, and local citizens need to be persuaded to connect to district heating infrastructure in the geographic target area. Additionally, Germany's mayors and local political decision-makers can contribute by supporting the initiators when communicating with the local public. At the national level, actors such as policymakers and interest groups need to ensure that the policy mix is favorable for the diffusion of new district heating systems (e.g., that target-oriented incentive policies are in place).

5.1.2. Interaction (networks)

Interaction is important at both the national level and the local level. At the national level, interaction and collective advocacy are key to ensure that the policy framework is shaped in ways that support the development of the district heating innovation system. However, in Germany, interaction has not yet led to forceful collective action to accelerate the development of the district heating innovation system significantly. Moreover, recent research shows that coalition building is not yet well established in the German heating sector.[2] This applies to the domestic heat sector as a whole, but is likely to be the case for the district heating innovation system too. To date, no interest groups have specifically advocated an accelerated diffusion of non-urban, low-carbon district heating projects.

At the local level, the project initiators need to build networks not only with local political decision-makers (to secure support for their project), but also with knowledge intermediaries, component suppliers, project planning companies, and local residents who ultimately will become customers. This situation contributes to the configurational character of technological innovation systems: local dynamics and conditions are heterogeneous and may require different interaction and communication approaches.

5.1.3. Institutions

As indicated in the theory section of this paper, we differentiate between hard institutions and soft institutions. The landscape of hard institutions in the German district heating innovation system is fragmented. A large number of financial support schemes provide funds for heating and district heating related technologies and components (co2online and Federal Minister for the Environment, Nature Conservation, and Nuclear Safety, 2019). These support schemes were implemented with the aim to drive down CO_2 emissions in the domestic heating sector. However, a number of the schemes continue to fund the implementation of fossil-fuel based heating infrastructure (co2online, BMU 2019). As a consequence, they perpetuate the fossil fuel lock-in. Apart from incentivizing the diffusion of low-carbon technologies, German legislation also allows local policymakers to implement some prescriptive regulations. However, when implementing such regulations, the leeway is quite narrow. The implementation of fossil-fuel heat technologies can only be restricted in newly developed neighborhoods in municipalities. However, our interviews with national experts suggest that this option is seldom used, and the major reason is the fear that the implementation would reduce the attractiveness of the municipality for investors.

Soft institutions differ regionally and are contingent upon implementation sites. In newly developed neighborhoods the connection to a district heating network is most often included in the real estate purchase agreement. Hence, buyers of construction sites often view the connection to a district heating network as one – often minor – characteristic of a construction site or building. Conversely, in preexisting neighborhoods, soft institutions play out with more force. Residents living in such neighborhoods seldom desire to change their heating infrastructure while the existing heating systems continue to operate, and the installation of new heating infrastructure involves extra effort, noise exposure, and sometimes high financial investments.

[2] Wesche et al. 'Actor coordination and division in sustainability transitions – evidence from the German domestic heat system', submitted to *Environmental Innovation and Societal Transitions*.

5.1.4. Infrastructure

With regard to physical infrastructure, district heating systems are strongly dependent on the local context. As is characteristic of configurational technologies, each implementation environment is unique. For example, a variety of heat sources is available for district heating systems, and the optimal choice for a given case depends on local conditions, such as the availability of waste heat. Compared with using oil as an energy source, a new district heating network may offer a competitive alternative in terms of price. Conversely, if a gas grid is operational in the target area, a new district heating network is unlikely to be able to offer attractive prices to local residents. Thus, the physical infrastructural contingencies not only substantially influence the design of a district heating project, but also influence the financial viability and hence the probability of its successful implementation. Apart from physical infrastructure, also knowledge and financial infrastructure are relevant for the implementation of district heating projects. For example, knowledge is crucial for deciding what components to use, how to interact with the local population, and what financial support schemes to exploit. Financial infrastructure that allows for access to loans is challenging, as non-urban heat grids are often implemented by lay initiators who do not have sufficient collateral at their disposal.

5.2. Systemic problems in project stages

As a next step in our analysis in this paper, we examine the development of non-urban heat projects in four development stages: (1) project initiation and group formation, (2) knowledge accumulation, (3) planning, and (4) securing demand. These stages are heuristics, which we used to structure the collected data. They represent the major tasks that need to be completed in order to implement non-urban district heating systems successfully. Furthermore, the four stages are not entirely disjunctive, but partly overlap and may include feedback loops. In the following subsections we briefly describe each stage and the present a synthesis of the major systemic problems it encompasses and how these problems hamper the performance of innovation system functions (for an overview of the identified systemic problems, see Figure 1, in the section ‘Functions performance’).

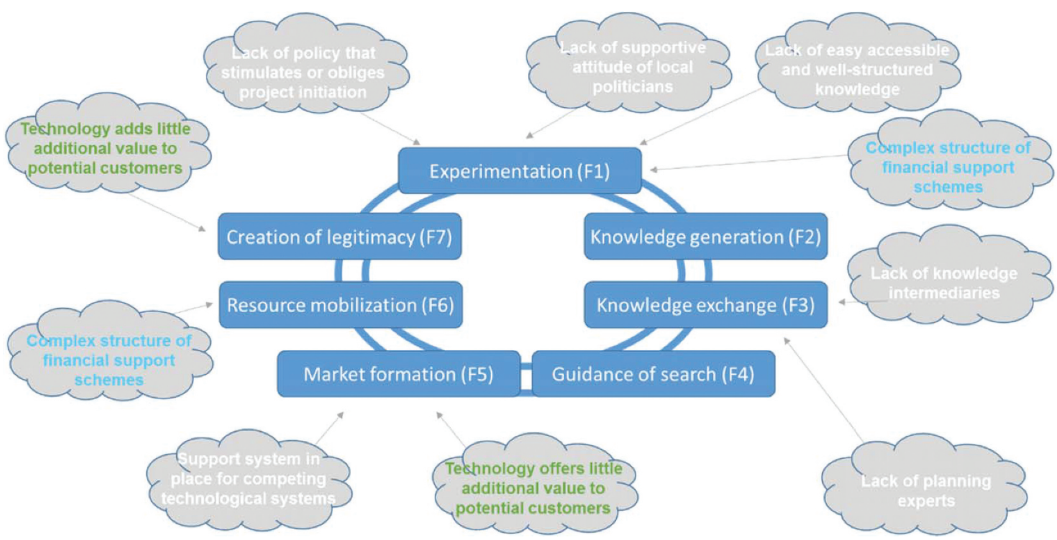

Figure 1. Systemic problems that hamper the functional performance of the German non-urban district heating TIS.

5.2.1. Stage 1: project initiation

The first stage of project initiation introduces the diverse set of factors that lead to the initiation of district heating projects. Our empirical data showed that all four studied projects were launched by small groups of like-minded individuals. The groups were very willing to invest time and effort in the implementation of a district heating system. In the case of project A (Table 3), local environmental group had lobbied for the implementation of a district heating system for several years, but it was only when an executive of a regional district heating system developing firm became aware of a feasible waste heat source that the project development process started. In the case of project B, a local community clerk had aimed to increase the attractiveness of his village and therefore started the initiation process together with an acquaintance who ran a renewable energy firm. Project C was initiated by a mayor who wanted to stimulate local economic development and to increase sustainability within his municipality. Project D was started by two local entrepreneurs who seized an opportunity to initiate a district heating system when upcoming roadworks in their town center were carried out.

The above-mentioned examples show that the initiation processes of the analyzed non-urban district heating systems were all serendipitous acts. There is no nationwide obligation for municipal heat planning. This reduces the willingness of local actors in municipalities to engage in district heating development. Thus, the first systemic problem is a lack of policy *that stimulates or obliges project initiation*.[3] This claim is supported by information from interviewees at the national level (ID #23, ID #29). To sustain the initiation process, the initiator teams usually sought and won support from local politicians, often local mayors[4]

> The local council must be positive about the project and help to promote it. (ID #19)

The support included both tangible and intangible assets. For instance, the support facilitated access to community-owned real estate (ID #19) or open endorsement of a project (ID #2, ID #19). The reason for mayors to support the local district heating systems were to attract new residents, decrease energy-related spending among the local population, and contribute to nature conservation (ID #11, ID #15, ID #18, ID #20):

> Increasing attractiveness, innovation, economic development, (and) contributing to environmental protection. This was the bundle of motivation. (mayor, project B, ID #11)

Even though all projects were supported by local politicians, the level of support differed. In projects B and C, the mayors were part of the core development team from the outset. They co-organized the first gatherings and helped to secure funding (ID #11, ID #15). The mayor in project D was not part of the core team, but like his counterparts in project B and C he actively supported the district heating project and convinced other members of the local council to back and endorse it (ID #18, ID #20). By contrast, in project A the mayor took a positive but rather passive stance (ID #4). He financed a feasibility study early on but took the position that local municipalities should focus on the provision of core services defined by law, while any other activities should be initiated and driven by market forces (ID #1).

Against the above-described background we identify the *lack of supportive attitude of local politicians* as a systemic problem that seemingly hampers the diffusion of district heating systems. This is corroborated by a statement from a national expert (ID #23, similar to ID #15)), who pointed out that, due to limited resources, mayors and members of local councils were inclined to restrict the action of their municipality to a minimum:

> Everything that is not a communal duty is directly put aside. (ID #23)

[3]In this subsection systemic problems are indicated in italic.

[4]In Germany, mayors are often the lowest administrative representative of the executive branch of the state. They are usually elected by the citizens of the municipality.:

Therefore, local political decision-makers are not likely to engage in activities to aid projects that are outside their clearly assigned tasks.

The analysis of the initiation phase revealed two distinct systemic problems. First, there is a *lack of regulation that specifically stimulates or obliges project initiation* by means such as obligatory heat planning. Seemingly, a well well-orchestrated project initiation process is missing. Second, project initiators seem to experience *different levels of crucial local political support*, which suggests that one reason for the limited number of new projects is likely to be an entire lack of local support. Both systemic problems hamper the experimentation function.

5.2.2. Stage 2: knowledge accumulation

Once a project has been launched, project initiators enter the knowledge accumulation phase to prepare for project planning. Hence, the second stage deals with the processes that project teams implement to acquire the relevant knowledge and information in order to prepare for project planning and implementation.

Successful implementation of non-urban district heating projects requires ample knowledge – often technical and regulatory knowledge. Technological knowledge includes knowledge about the functionality of specific technologies, configurability of and interplay between technologies, and the market availability of technologies and components. Regulatory knowledge includes knowledge not only about municipal regulation, but also about specific financial support schemes. Apart from technological and regulatory knowledge, project initiators require knowledge that is more context-related, such as information about the local heat demand and potential supply sources (ID #2, ID #3, ID #4, ID #8, ID #9, ID #13, ID #18, ID #19).

The interviewees reported that the collection of knowledge was sometimes an intricate process due to technological and regulatory knowledge being dispersed, fragmented, and not easy to locate. This led to the need for substantial efforts to gather all essential pieces of information. Sometimes, project initiators struggle to gather the right information for their project. For instance, in project A, local initiators had struggled to find out what data they needed to collect locally. Since they did not know what information to collect, the data they collected proved to be useless later on in the implementation process (ID #3, ID #4):

> They collected infrastructure and consumption data when they found someone at home. [Data for] other buildings were more or less estimated. However, we [as project developers] can't base a project [planning process] on this kind of data. (ID #3)

The quote points to another systemic problem, namely the *lack of easily accessible and well-structured knowledge*, which hampers the experimentation function.

Initiator teams can choose between two approaches to collect knowledge: either they can draw on intermediary organizations, or they can try to take care of the knowledge accumulation process themselves. The latter strategy is likely to increase the probability of project success, since lay initiators might be overwhelmed by the amount of the knowledge required (ID #4, ID #8, ID #3, ID #11).

The project development in project A shows the integral role that a knowledge intermediary (in the case of the project, a general contractor) can play in the success of non-urban district heating systems. An initiator group had established itself at the beginning of the year 2000 (ID #2, ID #3, ID #4), and it had successfully lobbied the mayor for approval to conduct a feasibility study. Furthermore, the group had held a number of public meetings and carried out door-to-door visits to houses, as well as collecting substantial data on the heat supply needs and willingness of households to connect to a potential district heating system. However, due to insufficient knowledge and resources, the project was put into hibernation until the beginning of 2014, when a general contractor was invited by a local businessperson and other residents to restart it (ID #1, ID #4). The general contractor took advantage of the knowledge that the company had acquired during previous district heating projects (ID #2, ID #3, ID #4). Once on-board, the contractor was able to implement the project in less than one year. Similarly, help for projects B and C was sought through intermediary organizations. For instance, the initiators of project B managed to establish cooperative ties with a regional technological university of applied sciences (ID #12, ID #13), while the initiators of project C took advantage of a regional business development agency that had some limited experience of district heating (ID #15, ID #16, ID #17).

In general, if project initiators choose to not rely on intermediary organizations, but to accumulate knowledge by themselves, they are likely to input substantially more effort. Only the initiators of project D were capable of pursuing this second approach. In that project, one of the initiators ran a renewable energy technology company and held several patents for thermal heat storage units (ID #19). His partner ran a software company that programmed the control unit for the district heating system (ID #29).

According to some interviewees, it was not easy to find appropriate intermediaries (ID #4, ID #8). Hence, our analysis suggests that a *lack of sufficient intermediaries that offer easy accessible and well-structured knowledge* can be seen as another systemic problem. Together with the earlier mentioned *lack of easily accessible and well-structured knowledge*, the lack of intermediaries with sufficient knowledge hampers not only the directly relatable knowledge exchange function, but indirectly also the experimentation function, as well as the knowledge generation function, as they both demand that ample knowledge exchanges take place.

5.2.3. Stage 3: planning

During the planning stage of district heating projects, both external and local knowledge are incorporated in viable project designs. Hence, project initiators need to ensure technological functionality, as well that the project design allows for attractive supply contracts for potential customers.

Similar to in the knowledge-accumulation stage of the project, initiators need to decide in the planning stage whether they want to involve experts or lead the planning process themselves. Involving experts is likely to lead to a faster implementation, as in the case of project A (ID #3). However, such experts rarely exist (ID #4 ID #17). This points to *a lack of planning experts* as another systemic problem and leads to insufficient support for planning and implementation of district heating systems. A higher availability of general contractors may be helpful to support initiators' teams and to increase the number of newly implemented non-urban district heating projects.

To create viable project plans, district heating system initiators require access to physical and financial resources. Physical resources encompass space to implement the district heating system, as well as market access to a diverse assortment of components. The interviews revealed that access to geographic space and availability of components were generally unproblematic. In non-urban areas, space seemed to be less contested than in urbanized areas. Furthermore, non-urban district heating system related components are probably readily available because they are also used in other technological systems. For instance, pipes and compressors that were installed in all analyzed projects have been used for years in district heating systems in large cities. Also, gas jet pipes, such as those installed in project C (ID #15), have been in use in the natural gas industry for many years.

Financial resources relate to access to direct financial support, for example through financial support schemes. With regard to such schemes, several actors shared the opinion that in general the German government grants sufficient funds (ID #2, ID #23, ID #28, ID #29). For instance, the CEO of the general contractor in project A stated:

> In the end, we get about a quarter to a fifth of the total investment as a grant, and I find that very generous. (ID #2)

Instead of asking for more government funds, the interviewees suggested to tackle both the *complexity of support schemes* and the *allocation of support funds for competing fossil fuel technological systems* (ID #23, ID #28, ID #29). Especially the allocation of financial funds to fossil-fuel based heating systems creates a contradictive institutional environment that leads to a lower level of relative attractiveness for low carbon technologies such as district heating systems (ID #2, ID #3, ID #6, ID #19, ID #20, ID #21).

Similar to the case of the lack of intermediaries (stage 1), the lack of planning experts directly hampers the knowledge exchange function, and indirectly the knowledge development and experimentation functions. The overly complex structure of support schemes hampers the resource mobilization function. Furthermore, the financial support for competing fossil-fuel based technological systems hampers the market formation function.

5.2.4. Stage 4: securing demand

To ensure financially viable operations, projects require a sufficient number of customers. If the share of the local population that become customers of a newly planned and implemented district heating system is insufficient, the business model will collapse and the system will fail. Therefore, once the first draft layout plan is ready, the project initiators' main task is to secure sufficient heat-related purchase agreements. This is not a trivial task, since often the existing heating infrastructure will still be operating well and local residents will not have an urgent need to change their heating technology. Furthermore, changing the heating infrastructure involves nuisance and requires extra effort.

Residents in existing neighborhoods in Germany often rely on an existing heat supply that works well, with a low level of effort required. At any given time, only a limited share of households in an area will need to replace their heating infrastructure, due to different age structures. Hence, the genuine demand for new heat technology in existing neighborhoods is often limited. In rare cases, the age of the local heating infrastructure is similar and needs to be replaced simultaneously. This was the case in project C, where a district heating system was implemented in a village in a rural area of eastern Germany when most fossil-fuel based heating systems that had been implemented after the fall of the Iron Curtain had reached their changeover date:

> Shortly after the fall of the Berlin Wall, all new heating systems were installed [here]. Now, about 20 years had passed, and the heating systems had worn out accordingly. Hence, demand for new infrastructure grew. People thought we either upgrade our old heating systems, or we just connect to the district heating system. (ID #17)

Our empirical data indicate that in the current state of innovation system development potential customers are often not likely to be interested in district heating systems because the *technology does not offer them any added specific value or because they have different needs*. For instance, some residents had a strong preference for being self-sufficient (ID #21). Others tended to favor investments in kitchens or bathrooms over investments in heating infrastructure (ID #21), which by default also decreased the funds available for investment in heating infrastructure. The lack of interest can be understood as a technology-related systemic problem, as the technology seemingly does not always offer substantial utility to potential customers. The market formation function and the legitimation function are both hampered by the lack of such utility.

Even though there may be several instruments, such as town hall meetings or door-to-door visits, to overcome a lack of interest in the scope of projects, the data show that regardless of the local context, project initiators in the studied cases used financially attractive contracts as their preferred means to secure sufficiently high connection rates (ID #2, ID #12 ID #13). This in turn points to the misconfiguration of policy instruments that currently limit the relative attractiveness of implementing district heating systems.

5.2.5. Functions' performance

The findings from our analysis suggest that most functions are not performing smoothly. Figure 1 presents an overview of the systemic problems that became apparent in the analysis and how they hampered the innovation systems' functions. Altogether, eight major systemic problems inhibited the take-off of the non-urban district heating innovation system in Germany. These eight systemic problems are depicted on the outermost ring in Figure 1 and point to the functions that they hamper. Two systemic problems are displayed twice because they each affect the performance of two functions (shown in the same colors). As mentioned in the theory section, poorly performing functions tend to influence each other negatively. Hence, the case of the analyzed non-urban district heating TIS suggests that negative mutual feedback loops keep functions from accelerating their performance. Even though there are some promising system structures, such as government goals and financial incentives, most functions continue to perform poorly and therefore also hamper the acceleration of development of other functions.

6. Discussion and implications

In this section we discuss the findings and draw implications for policymaking to accelerate the development of configurational TIS based on the TIS analysis of the non-urban heat system in Germany. We also look at how to design specific policies to stimulate the development of the country's non-urban district heating TIS.

6.1. Non-urban district heating in Germany

The findings from our analysis support the categorization of non-urban district heating TIS as a configurational TIS. The factors that triggered each of the four case projects, as well as the choice of the heating source, all depended on the local context and existing actor constellations. Overall, the analysis reveals the impediments to the development of non-urban district heating systems and the systemic problems hampering these systems' take-off. Smart innovation system structures that would enable the development of virtuous cycles are missing too. For example, easily accessible and well-structured knowledge is lacking, as are intermediaries that could make such knowledge available. Furthermore, as the financial support for fossil fuel technologies is still high and there is only moderate support for renewables-based non-urban district heating, there is no real incentive for local project initiators or politicians to engage in the implementation of non-urban district heating systems. Overall, the conclusion can be drawn that the non-urban district heating TIS in Germany is still in its infancy, and that a supportive institutional environment similar to the one developed in the 1990s and 2000s for solar PV and wind energy (Dewald and Truffer 2012; Koch and Büchner 2016) still needs to emerge.

6.2. Policymaking to advance the development of configurational tis

In line with the theoretical reasoning that national policies can construct an overall supportive framework, we found that the systemic problems in configurational innovation systems are likely to be especially prevalent at local level, and that policymaking should give due consideration to their stronger local context dependence. Therefore, to accelerate the development of configurational innovation systems, policies need to establish smart innovation system structures that not only create a supportive environment for diffusion, but also decrease complexity and enable local actors to manage the high degree of context specificity. For example, policies could aim to select the most promising alternatives based on their technology readiness or sustainability potential, and direct policy measures toward those solutions in order to reduce the number of differing alternatives. Additionally, complexity could be reduced by proactively implementing policies that would decrease the attractiveness of unsustainable options. However, this should only be done under the condition that sustainable alternatives are readily available. Another promising strategy would be to support the facilitation of horizontal and vertical knowledge exchange. Horizontal knowledge exchange is crucial in local context-dependent configurational TIS, due to the diversity of applications combinations; this makes it challenging to choose optimal solutions. Thus, actors responsible for implementation have a special need to learn about solutions from each other. Vertical knowledge exchange refers to information flows across administrative levels, such as between the national and local level. This type of exchange is specifically needed in configurational systems, as due to the variety of local contexts, policymakers may be challenged to have an adequate overview of all potential solutions. Furthermore, vertical knowledge exchange could facilitate component manufacturers' knowledge of what components to focus their research and development activities on in order to prepare for market diffusion, and it could make installers aware of what emerging solutions they should become knowledgeable about. One way of facilitating knowledge exchange is the creation of dedicated knowledge intermediaries to support local actors who deal with the large variety of local contingencies and needs in different projects. These intermediaries could make knowledge available by offering easily accessible and on-demand advice to all actors that are considering the implementation of a configurational technology. Complementing these intermediaries, vertical knowledge exchange could be facilitated by ministries or other governmental bodies that organize forums where local actors can share experiences and bring their concerns to the attention of policymakers at the national level.

6.3. How to accelerate the diffusion of non-urban district heating systems in Germany

Drawing on the above theoretical implications for policymaking, we propose the following measures to create innovation system structures that could help to accelerate the development of non-urban district heat TIS.

First, our analysis shows that the projects suffered indirectly from the financial support for heating technologies based on fossil fuels and from complex financial support structures. Therefore, a logical improvement would be to reduce the support for such heating technologies and, if possible, increase the financial incentives to implement district heating and other heating systems based on renewable energies. Furthermore, policymakers should revise the current financial support schemes to reduce their complexity for applicants.

Second, our analysis shows that all four projects suffered both from a lack of policies to support project initiation and from the non-supportive attitude of local politicians, which hampered the project initiation process. To overcome this challenge, municipal heat planning should become a compulsory component of municipal services, and reduction targets for carbon emissions should be set at municipality level. Furthermore, venues where vertical knowledge exchange can take place should be established to support the search for suitable policy designs and to make knowledge available. Such approaches specifically cater to the needs of configurational TIS.

Third, sufficient heat density is a basic prerequisite for the successful implementation and operation of a local heating network. In order to guarantee sufficient heat density, it should be made possible to impose connection-and-use restrictions or combustion bans for the area where a new district heating project is to be implemented. To avoid overburdening low-income households, this could be implemented only in new housing developments or by providing additional financial support to ensure these households could manage the transition.

Fourth, the analysis shows the substantial need for support with the complex knowledge environments that are typical for a configurational TIS. As mentioned in the analysis section, the regulatory environment is highly complex and designing a suitable solution can be challenging for local actors due to the strong dependency on the local context and the large variety of available components and project designs. To support local actors in dealing with such complexities, the number of knowledge intermediaries should be increased, such as local or regional energy agencies that have the necessary heat-related knowledge. Their core task would be to stimulate the knowledge exchange among project initiators, local political decision-makers, and the potential users of district heating systems.

7. Conclusions, limitations, and further research

The conceptual aim of this paper is to contribute to a better understanding of how to formulate adequate policies to accelerate the development of configurational TIS. The empirical aim is to analyze what hampers the diffusion of the non-urban district heating innovation system in Germany.

The paper offers comprehensive insights into how to expand our conceptual understanding of configurational TIS. Additionally, it highlights the difficulties and weaknesses of the current development of the German non-urban district heating TIS.

Based on our empirical analysis, we have shown that when analyzing configurational innovation systems, it is sensible to take the specific local conditions of experiments into account and integrate them into the data collection. Adopting such a local context-sensitive collection approach helps to acquire not only data from the national level, but also a thorough understanding of the high number of local context-related obstacles. By taking such an approach, analysts should be able to provide a more holistic understanding of the focal TIS.

Based on the wider importance of the local context in configurational TIS, we have shown that policymaking to accelerate the development of configurational TIS should echo the local context dependency. In particular, it is apparent that the sole focus of national-level policies that do not take the local context into account is insufficient to overcome the multitude of local context-related obstacles. Therefore, to facilitate the acceleration of configurational innovation systems, policymakers aim to identify the most promising solutions, for example based on their technology readiness or sustainability potential, and then direct policy measures toward those solutions. Complementarily, they should implement policies that aim to reduce the number of configurations. Furthermore, since implementation environments are seldom identical, policymakers should not only make sure that knowledge is vertically exchanged, but also specifically safeguard enhanced knowledge exchange between local contexts, so that actors will have the opportunity to exchange experiences from similar local contexts (horizontal knowledge exchange).

The comprehensive set of policy recommendations made in this paper could lead to an increase the pace of the innovation system's development in Germany. However, it is evident that the implementation of such policy recommendations is not necessarily an easy process, and it will only unfold over time. Furthermore, our recommendations are still of a high-level nature and will require substantial effort to be converted into more detailed policies. The presented analysis and conclusions drawn in this paper should contribute to filling the gap in knowledge and understanding with regard to what influences the diffusion of non-urban district heating systems in Germany and beyond.

The limitations of our analysis relate mainly to the limitations of our empirical approach. First, an even broader empirical basis (number of interviews und projects studied) could have led to additional results. However, the choice of the four projects was theory driven to represent heterogeneity in combination with the national-level view, and therefore we considered the database sufficient for our aim. Second, probably the most important shortcoming is that we only studied successful cases, yet unsuccessful cases might have revealed further systematic problems. However, in practice it is hardly possible to identify and/or approach failed projects. Again, we tried to mitigate this issue through the national-level interviews.

We see valuable avenues for further research. On a theoretical basis, we suggest that further empirical analyses of other configurational TIS should be performed in order to confirm our findings. On an empirical level, we suggest that, first, ways to investigate unsuccessful projects should be developed in order to understand what issues made them fail. Second, a comparison between the German case and the Danish case of district heating would be of interest in order to learn what factors helped the Danish case to develop substantially faster in recent decades.

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