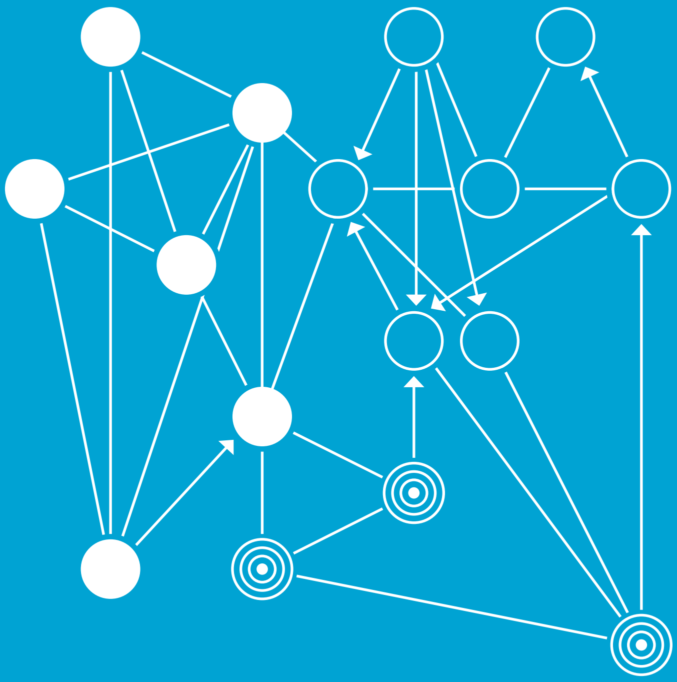

Configurational Innovation Systems

Transition Dynamics and Actor Strategies in the German Heat Sector

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CONFIGURATIONAL INNOVATION SYSTEMS

Transition Dynamics and Actor Strategies in the German Heat Sector

Konfigurationelle Innovationssysteme
Transitionsdynamiken und Akteurstrategien im Deutschen Wärmesektor

(mit einer Zusammenfassung in deutscher Sprache)

Configurationele Innovatiesystemen
Transitiedynamiek en actorstrategieën in het Duitse warmtesector

(met een samenvatting in het Nederlands)

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Scientific summary

Germany's Energiewende (energy transition) has been praised as a successful transition, as it is decarbonizing the country's energy system relatively quickly. Germany is phasing out its nuclear reactors, turning to renewables, and has implemented a strategy to phase out the use of coal for electricity generation. However, from closer consideration of the term "energy" and the related processes in Germany, it is apparent that while the transition has taken place in the electricity sector, much less has been achieved in other sectors such as the heating sector. This is surprising, given the similarities between the heating and electricity sector: Both systems are embedded in largely the same national, geographical, political, societal, and institutional environments. The observed differences in development are addressed in this thesis with respect to the following research question: *Why can transitions in very similar sectors unfold at very different speeds?*

This thesis draws on interdisciplinary concepts from the field of sustainability transitions. In the first half of the thesis the focus is on analyzing the structural characteristics of the German heating system. This part contains two qualitative interview studies. The first study compares the German heat transition with the German electricity transition, while the second study zooms in on district heating as a specific heating technology. The second half of the thesis focuses on contributing to a better understanding of actors and agency in order to find solutions to the differences in the pace of energy transitions in different sectors. To this end, the third study uses network data and qualitative interviews to analyze the interaction and coordination between heat technology lobby groups. The last study presents a literature review that compiles which factors influence actor coordination and which steps actors can choose to collectively advocate for sustainability transitions.

The technological innovation system (TIS) framework is used to analyze the structural characteristics of the German heating and electricity sector. The TIS framework allows for a thorough system analysis of the emergence and diffusion dynamics of technological innovations. Based on such analyses, insights can be drawn into what impedes the diffusion of innovations and what measures can be adopted to stimulate the diffusion of an innovation. Since a key condition for sustainability transitions is the diffusion of innovations that can provide goods and services in a more sustainable way, it is reasonable to use the diffusion-focused TIS approach to answer the research question in this thesis.

The German heating transition cannot be properly understood without adaptations in the TIS approach. An important insight is that the country's heating transition is strongly influenced by the local context where change needs to take place. Since heat cannot be transported inexpensively, the generation and demand for heat are highly geographically coupled, and the capacity for generating heat must be implemented locally. Due to this need for local implementation, the local context will substantially influence the selection and implementation of heat generation technology. As each building is unique, each newly installed heating system will need to be configured specifically to fit the local contingencies. By contrast, as electricity can be transported over long distances via electricity grids at low cost, supply and demand are geographically decoupled, which allows for implementation to occur where it is easiest. The implementation of electricity technologies such as wind turbines and solar PV panels requires less specific adaptation to the local context and hence these technologies are easier to be produced in series and thus at scale, which leads to price degression and hence fuels implementation.

Based on the background presented above, and on the work of Fleck (1993), heating technologies are denoted as configurational technologies and electricity technologies as generic technologies. Utilizing this differentiation, this thesis introduces the notion of configurational innovation systems (configurational TIS) as TIS that evolve around configurational technologies and generic innovation systems (generic TIS) that evolve around generic technologies. The thesis extends the body of knowledge on TIS by showing that configurational TIS are likely to develop at a slower pace than generic TIS.

While the differentiation between generic innovation systems and configurational innovation systems is relative in terms of scale, it has repercussions for the defining pillars and key processes of technological innovation systems: Due to their stronger local context dependence, configurational TIS feature more fragmented actor structures, interaction, and institutions. The empirical evidence presented in the thesis suggests that due to this more fragmented structure, configurational TIS are prone to problematic development patterns that hinder a rapid diffusion of more sustainable innovations, as well as transitions more generally. For example, as new heating technologies need to take more local contingencies into account, they cannot be as standardized as electricity technologies, which in turn leaves less room for the emergence of dominant designs that can be produced and implemented at scale by a relatively small number of actors. Furthermore, due to differing local contexts, different heating solutions have emerged in Germany, each of which are supported by a substantial number of distinct lobby groups. Uniting these rather diverse groups of actors to facilitate the emergence of legitimacy and to lobby for a clear and financially supportive policy framework is harder than is the case for the more compact group in generic electricity TIS.

The differentiation between configurational TIS and generic TIS is developed in two studies. While the first study compared the development of the rather configurational German heating TIS with the rather generic German electricity TIS, and developed the notion of configurational TIS, the second study focused on district heating systems as a specific type of configurational technology.

The development of a TIS is not only influenced by the systemic character of a TIS, but also by the ways agents make use of their agency. Furthermore, the system differences between generic TIS and configurational TIS can be expected to be influential in the context in which agents in these systems operate. Hence, from an academic point of view, it is interesting to develop a better understanding of how agents operate in configurational environments. Accordingly, whereas the first part of the thesis focuses on introducing and substantiating the concept of configurational innovation systems, the second part of the thesis puts actors center stage and focuses on the agency that actors exert in configurational TIS.

In a third empirical study, the coordination behavior of industrial groups that supported a number of distinct heating solutions was analyzed. The results indicated that the fragmented structure of configurational systems not only influenced the systemic development patterns, but also substantially influenced agency and coordination. Due to a more fragmented actor structure, coordination in configurational systems is likely to feature a larger number of different interests and visions. Such variety of interests and visions is not detrimental to TIS development in principle, but it is problematic in that coordination of a larger number of fragmented actors is seemingly more difficult. As a result, due to substantial variety of interests and visions, the thesis shows that a comparatively large number of small coalitions can emerge in configurational TIS. It is rather challenging to merge such coalitions into a strong coalition that promotes sustainable change.

After having contributed to a more thorough understanding of agency and coordination in configurational innovation systems, the thesis aims to contribute to a better understanding of coordination on a broader level and to draw conclusions as to how actors can build stronger coalitions in order to accelerate sustainability transitions. To do so, a literature review of the Advocacy Coalition Framework (ACF) is presented. The ACF is one of the most established policy process frameworks and holds that the policy process is substantially shaped by collective groups that by coordinating influence the outcomes of the policy process. While the fundamental notion of the ACF is that actors are drawn together by similar beliefs, the literature review in the thesis suggests that recent contributions paint a more nuanced picture. Next to similar beliefs, also trust plays a major role, and actors seem to be motivated to coordinate by a number of other motives, such as the urge for political power, access to resources, and access to the competence of other actors. Furthermore, the findings from the literature review lead to the suggestion that a fundamental prerequisite for coordination is that actors need to have the opportunity to meet and engage with each other. Such opportunities can, for example, be provided by coalition brokers. On this basis, while the initial understanding somewhat implicitly suggested that actors with similar beliefs would by default flock towards each other, this newer understanding is that coordination does not happen by default and that brokerage can be seen as an initial facilitator of coordination. This new view of coordination also has implications for the development of configurational TIS. Since the actor structure in generic TIS is likely to be rather compact, it facilitates for actors to meet each other, for example at industry meetings or through political dialogues. Hence, in such systems, brokers are likely to be able to help coalitions to institutionalize, but they might not be as fundamentally important as in configurational TIS. By contrast, actors in configurational TIS are less likely to know about each other, or of places where actors can meet, such as across geographies and administrative levels. Hence, as a conclusion, the need for well-connected brokers that organize and provide venues for exchange and networking is likely to be substantially higher in configurational TIS than in generic TIS. Apart from contributing to a better understanding of coordination, the findings from the literature review suggest a model of coalition interaction that opens up new avenues for further research and a number of hands-on recommendations on how to build impactful coalitions.

The thesis concludes that context dependence is an important factor that should be considered when studying and influencing sustainability transitions. It clearly impacts the dynamics of change and the agency of actors, as coordination of strategies and actions is much more difficult. The framework of configurational innovation systems may be helpful both to capture transition dynamics in situations where local context plays an important role and to explain speeds of transitions. The influence of local context is also a key explanatory variable that accounts for why the German heating transition has evolved so much more slowly than the transition to renewable electricity.

Introduction

1.1 Intellectual challenge

The world is rapidly globalizing and accelerating its economic development. Alongside the known positive consequences of this process, such as improved living standards, there are a multitude of challenges associated with key service systems such as electricity, heating/cooling, and transport. The ways in which these services are provided on a global scale exceed the planet's boundaries and threaten the basic living conditions of the human species (Rockström et al., 2009). Specifically, global energy and transport systems release greenhouse gases into the earth's atmosphere, which is linked to a highly probable rise in the earth's temperature to an unprecedented degree (IPCC, 2014). These unsustainable developments represent an unmatched threat to humankind. To avoid the worst impacts, societies must urgently embark on a profound decarbonization process, transitioning from currently unsustainable systems to sustainable ones (IPCC, 2014). Such sustainability transitions are difficult and complex processes, as they include a profound de-alignment and realignment of technical and institutional elements (Geels et al., 2017). To have a better understanding of transitions and the underlying dynamics, researchers have contributed to a substantial body of literature over the last two decades (for two overviews, see Markard et al., 2012 and Köhler et al., 2019).

Empirically, transitions develop with different dynamics and at different speeds. For example, the German Energiewende is regarded as one example as the ongoing transition of the German energy system is taking place very quickly (Geels et al., 2016; Matthes, 2017; Quitzow et al., 2016; Strunz, 2014). Germany is phasing out the use of nuclear energy (Bruninx et al., 2013; Glaser, 2012), turning to renewables (wind energy in Germany was the strongest single energy source, accounting for 52% of all renewable electricity sources in 2019 (AGEB, 2020), and has even formulated a plan to phase out the use of coal (Oei et al., 2020). However, from looking more closely at the term "energy" and the related processes in Germany, it is obvious that the transition mainly affects the electricity system; much less has been achieved in other sectors, such as the heating system. Although Germany's heating system is responsible for about 15% of the total greenhouse gas emissions in the country (BMWi, 2021, p. 21), its transition to a low- carbon system has been developing much slower than its transition in the electricity system: The share of renewable energy production increases every year in the electricity system, whereas the share of renewables in the heating system has not changed substantially over the last decade (BMWi, 2021). This is surprising, given the similarities between the heating and electricity sectors and the fact that they are embedded in largely the same geographical, political, and societal environments. This observed difference in development pace and the lack of a theoretical explanation for it to date prompted the intellectual challenge of this thesis and motivated the scholarly enquiry behind it.

1.2 The German heating system

The German heating system is dispersed and its decarbonization is crucial if Germany is to meet its emission reduction goals. The German building stock encompasses about 19 million residential and non-residential buildings (DESTATIS, 2019, p. 10). About 15% of all CO_2 emissions in Germany can be attributed to heat applications in those buildings (BMWi, 2021, p. 121). This means substantial efforts are required if the German government wants to achieve its target of a de facto climate-neutral building stock in 2050, as proposed in its report on the energy transition concept (BMWi, 2021, p. 51).

Buildings in Germany are traditionally heated by coal, heating oil and natural gas. As a result, these fossil fuel technologies still supply heat to more than 80% of German buildings (BDH, 2019). The building stock has not undergone any substantial changes in recent decades (BDH, 2019, 2020). Even though there is now a visible shift towards the use of heat pumps in new buildings, which can be powered by using renewable sources of energy, the share of buildings supplied with renewable energy is increasing very slowly due to a low overall renovation rate (BDH, 2020).

Technological solutions to provide space heating and warm water based on renewable energy sources have been developed and are widely available, but their diffusion is much slower than the diffusion of renewable electricity innovations. Solutions for single buildings include the use of wood pellets and biogas combustion units, solar thermal appliances, and different heat pump systems, such as air- or water-based systems, either in combination with or without solar PV. Additionally, complementary renewable technology solutions have been developed for heat networks that supply multiple buildings. These run on geothermal or solar thermal heat, waste, biogas, biomass, or large-scale heat pumps. However, even though the German government has implemented substantial financial support schemes to incentivize renewable heat alternatives, in addition to higher insulation standards, these renewable alternatives are diffusing only slowly, especially compared with the diffusion of renewable alternatives in the electricity system (Figure 1). This is astonishing, as the German heating and German electricity systems are not only set in the same national and geographic context, but are also exposed to the same political, social, and institutional developments.

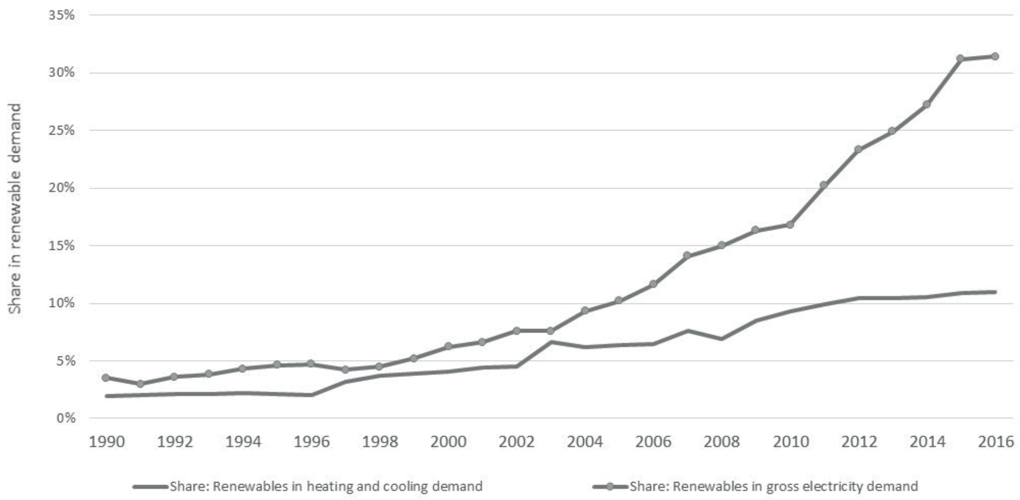

Figure 1: Shares of renewable energy in gross electricity consumption and share of renewables in final energy consumption for space heating and warm water (and cooling) (AGEE-Stat, 2020)

It can be assumed that the diffusion of renewable electricity technologies has been accelerated by external drivers. Two major driving forces of the German electricity transition are the nuclear incidents in Harrisburg and Chernobyl (Downing, 1988; Nelkin and Pollak, 1980; Rucht, 1990) and the reports of acid rain in Scandinavian countries as a result of substantial coal combustion in Germany (Boehmer-Christiansen and Skea, 1991; Jones, 1993). Both driving forces have led to the development of a strong antinuclear and pro-environmental movement in Germany (Dewald and Truffer, 2011).

However, when comparing the heating system with the electricity system, it becomes clear that there is a major systemically endogenous difference between the two systems beyond the strong and well organized pro-environmental movement. In the heating system, supply and demand are more strongly intertwined geographically than is the case for the electricity system.

The reason is that, although heat can be physically transported, the associated costs are so high that the transport of heat over distance is not financially viable. Therefore, heat needs to be made available in a building itself or in its immediate vicinity. By contrast, the transmission of electricity is easily and cheaply possible via high-voltage grids with low physical losses. As a result, the provision and consumption of electricity is geographically decoupled. This structural difference leads to a higher context dependency in the heating system than is the case in the electricity system. This difference is discussed briefly below.

The energy transition in the heating system mainly takes place in the stock of existing buildings. While new buildings are constantly being constructed, the share of newly installed heating systems – about 300,000 per year (DESTATIS, 2020, p. 9) – is a minor challenge compared with refurbishing the ca. 19 million existing buildings in the building stock.

Changing the heat supply in existing buildings is much more dependent on local contingencies than is the case when changing the electricity supply. All buildings in the building stock already have a heat supply. Therefore, when new heat solutions appear, their diffusion is influenced by the local contingencies that fitted the previous heating solutions and that need to be taken into account. As an example, if a building is to be retrofitted and the heating infrastructure is to be replaced with a new type of heat technology, not only will the heating infrastructure itself need to be replaced, but usually also adjacent elements. For example, if a gas boiler is to be replaced by a heat pump, not only will better insulation of the walls and roof be needed, but also replacement of the existing radiators with panel radiators, and it will be necessary to ensure that the building's electric systems are up to date. Additional social and material factors come into play in the local context when a heat supply system is to be exchanged. It is simple to switch electricity supply online, even for one household within an apartment building. By contrast, when exchanging the heat supply, other residents in the same building will influence the implementation process, as the entire building will be affected. They may not be affluent enough to support the overhaul necessary to implement a new heating system or they may simply not see the need to do so. Additionally, the availability of grid-related infrastructure such as district heating networks or gas grids influences the choice of heating system. Due to these local context dependencies, heat solutions vary widely, and while components may be standardized, their layout differs from building to building. By contrast, electricity technologies can be implemented anywhere and are influenced by preexisting local solutions to a much lesser degree. Their diffusion is also independent of other technologies' life cycles and local path dependencies. Furthermore, since electricity generation capacity does not need to be customized to the local context, dominant designs develop more quickly, are highly standardized and manufactured on an industrial scale. For example, by the 1990s, the horizontal-axis three-bladed design in the wind industry and Multi-Si, as well as Mono-Si technologies in the solar PV industry, had developed into dominant designs (Johnson and Jacobsson, 2003, p. 203). Once these dominant designs had emerged, it was possible to standardize and produce the technologies at scale and conduct a massive rollout. Wind turbines and open-space solar plants can be installed away from the points of electricity demand. The only exceptions are rooftop PV systems, which are implemented on buildings. However, these systems do not detract from the fact that electricity technologies decouple supply and demand geographically, since they can still be mass produced in a standardized manner and do not require local customization. The only requirement is that they need to be installed at a certain inclination, and rooftops are very suitable for this purpose.

The difference between the largely context-independent innovations in the electricity system and the strongly context-dependent ones in the heating system resembles what Fleck (1993) calls generic and configurational technologies. Based on examples drawn from robotics, production systems, and IT applications, Fleck (1993) suggests that generic technologies feature a low level of context dependence, whereas configurational technologies feature a high level of context dependence. According to Fleck (1993), this difference in local context dependence leads to the different characteristics of the technologies and influences their diffusion (Fleck, 1993, pp. 17–18). In this thesis, the differentiation between generic and configurational technologies is used to increase the understanding of the German heating and electricity systems, and to explain their different development dynamics.

1.3 Aim of the thesis

While the sustainability transition literature has expanded substantially over the last two decades (Köhler et al., 2019; Markard et al., 2012), the role of local context dependence and its implications for technological innovation system (TIS) development in particular and sustainability transitions in general have not been conceptualized. While the literature acknowledges that technological innovation systems are generally influenced by exogenous factors (Bergek et al., 2015), the degree to which local contingencies influence the diffusion of innovations has not been analyzed nor understood. This is surprising, as the local context is likely to play a major role in the place of implementation. This may not only be the case for the diffusion of heat-related technologies, but could also influence the transition in the mobility system, where the possibility to implement charging infrastructure is influenced by, for example, local contingencies, as well as the transition of the agro-food system, in which climate, soil quality, and local industry structures have major impacts on transition dynamics (Vermunt et al., 2020). The aim of thesis is to contribute in this respect. To do so, the first part of the thesis defines a new type of innovation system that specifically accounts for local context dependencies – the configurational innovation system.

Considering that local context dependence has repercussions on transitions in general and particularly on how technological innovation systems are shaped, the systemic environments that actors operate in are likely to differ depending on the type of system involved. Therefore, as actors play a key role in systems transitions, it seems promising to explore how actors behave and coordinate in different environments, and how they try to shape these institutional environments. Hence, whereas the first part of the thesis focuses on conceptualizing and understanding configurational innovation systems from a systemic perspective, the second part focuses on actors in order to gain a better understanding of their behavior in configurational systems. More specifically, the aim in second part is to analyze empirically how actors use their agency to shape their institutional environment in configurational settings, and to compile literature on actor behavior and what influences actors to coordinate in order shape institutions. Concerning what influences actor behaviour it will be analysed what can be learned from the Advocacy Coalition Framework (ACF) and how the coordination-related insights of the ACF can be used to gain an understanding of the development of configurational systems, as well as of sustainability transitions in general.

1.4 Sustainability transitions

In light of the increase in environmental and societal challenges such as climate change, biodiversity loss, and resource depletion (e.g., clean water, petroleum, forests, and fish stocks) over the last two decades, a substantial body of literature has evolved that deals with understanding and explaining how transitions to more sustainable systems are possible. These environmental problems are caused by unsustainable processes of consumption and production in socio-technical systems. Examples of systems that are currently operating unsustainably include electricity, heat provision, mobility, and agricultural produce in the form of food. The outlined challenges cannot be addressed through incremental improvements and technological short-term solutions; they require radical change. Current systems of production and consumption need to be replaced by novel socio-technical systems (Markard et al., 2012). The elements of the socio-technical systems in question need to be de-aligned and subsequently realigned so that more sustainable operating patterns emerge. Such fundamental and, at the same time, guided de-alignment and realignment of socio-technical system elements can be referred to as "sustainability transition" (Elzen et al., 2004; Geels and Schot, 2007b; Smith et al., 2005).

Kohler et al. state that the "central aim of transitions research is to conceptualize and explain how radical changes can occur in the way societal functions are fulfilled" (Köhler et al., 2019, p. 2). The focus of sustainability transitions research is different from the longstanding debate on sustainability at the "micro" or "macro" level. The unit of analysis for sustainability transitions research is primarily the "meso" level of socio-technical systems (Geels, 2004). This makes it possible to analyze and explain change in a structural and procedural manner that is independent of individual action (micro level) and does not require an exhaustive de-alignment and realignment of the entire system and its institutions (macro level).

Sustainability transitions entail a number of characteristics that are complex and challenging to conceptualize. They are complex because they are long-term processes involving an unknown number of actors, institutions and material artefacts (Rotmans et al., 2001), which co-evolve along a multitude of dimensions (Geels, 2002). Furthermore, transitions can develop along several trajectories and pathways (Geels and Schot, 2007b) and may lead to lock-ins (Unruh, 2000; Walker, 2000). Hence, their outcomes are highly uncertain (Moallemi and Köhler, 2019; Rosenbloom, 2017).

Over the last two decades, a number of frameworks have emerged in the field of sustainability studies (Markard et al., 2012). These include the multi-level perspective (MLP) (Geels, 2002, 2004), the technological innovation system approach (TIS) (Bergek, Jacobsson, Carlsson et al., 2008; Hekkert, Suurs et al., 2007), strategic niche management (SNM) (Raven, 2005), and transition management (Loorbach, 2010; Loorbach and Rotmans, 2010). They all adopt a systemic perspective to capture co-evolutionary complexity and key phenomena such as the emergence of novelty, path dependence, and nonlinear diffusion dynamics. In the following, the multi-level perspective (MLP) is adopted as the framework that offers a compelling holistic representation of the key processes of sustainable transitions (Geels, 2002, 2004).

The MLP views the transformation of socio-technical systems as resulting from the interplay of three different levels: (1) the sociotechnical *regime*, (2) expanding innovations at *niche* that diffuses to become widespread, and (3) the *landscape*, which is the exogenous environment in which socio-technical systems are embedded. The three levels are intertwined and constantly subject to de-alignment and realignment processes (Geels et al., 2017). They represent the basic processes that are necessary for a transition.

First, the socio-technical regime refers to the semi-coherent set of "relatively stable configurations of institutions, techniques and artefacts, as well as rules, practices and networks that determine the 'normal' development and use of technologies" (Smith et al., 2005, p. 1493). It encompasses all socio-technical elements, as well as their connections and interactions. For example, in the case of the residential heating system, the regime encompasses not only heating technologies and insulation materials, but also all heat-related actors (e.g., industry groups, NGOs and politicians) and (support) policies and heating-related norms. Over time, these elements have evolved into an interwoven socio-technical fabric, which stabilizes the dominant pattern of heat provision. For example, in recent decades, natural gas-fueled condensing boilers have developed into the dominant application for heat provision in the German residential heat market. Together with policies supporting natural gas and installer preferences, natural gas- based heating systems form the deep structure (the regime) of the German heating system. Although regimes are stable and display substantial inertia, they almost always feature cracks and tensions. Cracks and tensions can be unfulfilled user needs, accumulating negative externalities (e.g., greenhouse gas emissions), and negative cultural discourses that undermine the legitimacy of a regime (Geels et al., 2017). In order to seal cracks and alleviate tensions, regimes need to change. Hence, even though regimes can be very stable, the cracks and tensions show that regimes continuously evolve. Depending on the magnitude of the cracks and tensions, the regime absorbs innovations differently. If cracks and tensions are of minor magnitude, innovations are only absorbed into the regime if they are of incremental character and allow for efficiency gains. If possible, incumbent regime actors often resist the intake of radical innovations due to lock-in mechanisms such as vested interests, institutional commitments, sunk investments, and core competencies that lead to path dependencies (Markard et al., 2012). For example, if the regime functions smoothly, large industrial players that have honed their production skills to produce gas-condensing boilers efficiently are unlikely to channel substantial research and development resources into renewable heat technologies. By contrast, when cracks and tensions amplify, regime actors are increasingly inclined to adopt radical innovations in order to fight against becoming obsolete. In such cases, the same incumbents are more likely to invest substantial funds into developing renewable heat alternatives if the alternative means being forced out of the market.

Second, niches are defined as protective spaces where novel solutions can develop and mature. In these niches, innovations are nurtured and protected from the selection environment (Smith and Raven, 2012). Rules for protection may relate to a specific geographical area (geographical niche) or to a specific part of the market (market niche). The financial support for renewable heat technologies mentioned above as a crack in the currently dominant institutional logic can be seen as such a market niche. For a transition to take place, such innovations need to become robust, develop and grow, and eventually replace non-sustainable regime configurations that are often supported by regime actors.

Third, the constant de-alignment and realignment that regimes and niche innovations undergo are substantially influenced by the surrounding exogenous environment. In the socio-technical transitions literature, this environment is referred to as the *landscape*. The degree of alignment between the rules of the landscape and the rules of the regime gives stability to a regime. If there is a high degree of alignment between the landscape and the regime, the regime can continue to perpetuate itself. By contrast, if there is a low degree of alignment between the landscape level and the regime level, the above- mentioned cracks and tensions will start to emerge and new windows of opportunity for niche innovations will open up. The supreme landscape development that is placing pressure on the heat regime in Germany is the debate about climate change. This pressure is likely to be responsible for some of the cracks and tensions in the current heat regime. However, so far, it has not created sufficient cracks and tensions for renewable heating alternatives to emerge.

As mentioned, the MLP is a strong perspective to apply when analyzing regime shifts and thereby portraying socio-technical transitions. However, it is weak for explaining how innovations (novelty) develop from a niche phenomenon to being at scale and thereby transforming the regime (Markard and Truffer, 2008b). Therefore, another framework has been introduced that deals specifically with the creation of novelty and the diffusion of innovations, namely technological innovation system (TIS) framework. Building on the TIS framework, the notion of the configurational innovation system has been introduced as a TIS that evolves around technologies that are strongly dependent on the local context.

1.5 Configurational innovation systems

Innovations do not develop in a vacuum (Carlsson and Stankiewicz, 1991); they are embedded in systems that influence the emergence and diffusion of innovations. Innovation systems can be defined as “a heuristic attempt, developed to analyze all societal subsystems, actors, and institutions contributing in one way or the other, directly or indirectly, intentionally or not, to the emergence or production of innovation” (Carlsson and Stankiewicz, 1991; Hekkert, Suurs et al., 2007, p. 414; Sagar and Holdren, 2002).

To date, several concepts have emerged that characterize the systemic nature of innovation with different foci. These include regional innovations systems (Cooke et al., 1997; Cooke, 2001), national innovation systems (Lundvall, 1995; Nelson, 1993), sectoral innovation systems (Breschi and Malerba, 1997; Malerba, 2002), and technological innovation systems (Bergek, Jacobsson, Carlsson et al., 2008; Carlsson and Stankiewicz, 1991; Hekkert, Suurs et al., 2007). Independent of the system’s scope, the main purpose behind the introduction of all four concepts was to develop a better procedural understanding of how the emergence and diffusion of innovations is influenced by the environments in which they are embedded. For this reason, none of the approaches distinguishes innovations in terms of their contribution to sustainable development.

As the research question in this thesis refers to the diffusion of technological innovations, the technological innovation system (TIS) approach is applied. Similar to the other innovation system concepts, the approach in the TIS concept does not distinguish between innovations in terms of their sustainability contribution. However, it does allow for a thorough analysis of the emergence and diffusion dynamics of technological innovations. Since a further aim of this thesis is to add to a more nuanced understanding of the diffusion dynamics of innovations, the

TIS approach is appropriate. Even though, originally, it was not specifically created to analyze the diffusion of sustainability-related innovations, over the past 10–20 years it has been applied, for example, to the diffusion of solar photovoltaics (Dewald and Truffer, 2011; Quitzow, 2015), wind power (Gosens and Lu, 2013), smart grids (Planko et al., 2016), biogas (Negro et al., 2007), bio refineries (Bauer et al., 2017), and district heating (Hawkey, 2012; Hawkey and Webb, 2014).

TIS features a comprehensive framework that allows for a thorough analysis of the emergence and diffusion processes of technological innovations. According to the TIS approach, a TIS consists of four types of structural component: actors, interactions, institutions, and infrastructures (Carlsson and Stankiewicz, 1991; Kieft et al., 2016; Markard and Truffer, 2008b; Wieczorek and Hekkert, 2012). First, actors are the individuals, organizations and networks, and their activities regarding the focal innovation, such as companies, knowledge organizations, non-governmental organizations (NGOs), civil society, government, and other parties (Wieczorek and Hekkert, 2012, p. 76). In the case of innovation systems for heating, these include not only the companies Bosch and Vaillant, the German Energy Agency (DENA), the German Federal Association for Renewable Energies, the German Federal Ministry for Economic Affairs and Energy, but also regional and local players such as households, mayors, small intermediaries, and individual heating system installers. Second, interaction takes place within networks or between individuals (Wieczorek and Hekkert, 2012, p. 77), such as company representatives of heating industry lobby groups. Third, institutions are defined as “the rules of the game.” The literature distinguishes between hard (also known as “formal”) and soft (“informal“) institutions. Whereas formal institutions have written rules concerning, for examples, policies, codes and strategies, informal institutions resemble non-codified rules such as common habits, routines, norms, and values, and shared concepts used by humans in repetitive situations (Crawford and Ostrom, 1995; Wieczorek and Hekkert, 2012). For example, formal institutions can be financial support policies for a number of specific heat generation systems. By contrast, an informal institution can be the willingness to connect to a district heating system or the ease of operating a newly installed heating system. The fourth structural component, infrastructures, encompasses three categories: physical infrastructures, financial infrastructures and knowledge (Wieczorek and Hekkert, 2012, p. 77). Examples of physical infrastructure are the existence of a gas grid or a district heating network in a given geographical area. An example of financial infrastructure is the access to loans for heat-related investments, whereas knowledge refers to the actors’ knowledge of the heating system and related processes.

An analysis of the structural components within an innovation system can offer insights into potential intervention points. However, focusing solely on the structures and comparing their specific configuration would lead only to quasi-static analyses and would neglect the dynamics of innovation systems. Thus, structural analyses are often coupled with functional analyses. A functional analysis explores the main processes that are necessary for an innovation to function. For example, recommendations for policies can be made based on the analysis of the functions. Although Bergek, Jacobsson, Carlsson et al. (2008) have introduced different sets of functions, a widely deployed set is that used by Hekkert, Suurs et al. (2007), which encompasses seven distinct functions: entrepreneurial activity (F1), knowledge development (F2), knowledge diffusion (F3), guidance of search (F4), market formation (F5), resource mobilization (F6), and legitimacy (F7). These system functions are not mutually independent but can reinforce or weaken each other. For example, new supportive policies (F4) can create demand (F5), which can then motivate more actors to engage in entrepreneurial activities (F1). Hence, in best- case scenarios, endogenous events mutually stimulate functional development and lead to virtuous cycles that accelerate the development of an innovation system (Hekkert, Suurs et al., 2007; Jacobsson and Lauber, 2006; Suurs et al., 2010). In turn, if functions are hampered and do not reinforce each other, such virtuous cycles are unlikely to emerge and an innovation system will be impeded.

The TIS literature has only recently started to acknowledge that technological innovation systems may differ structurally and that this may influence TIS dynamics. For example, Stephan et al. (2017) suggest that when such systems evolve around multi-component technologies they are more likely to encounter problematic dynamics than in the case of single-component technologies. As another example of differing types of TIS that evolve with differing dynamics, Binz and Truffer (2017) suggest that different TIS may feature distinctly different types of innovation and knowledge generation processes. They highlight the importance of different learning types and distinguish a science, technology and innovation (STI) mode and a doing, using and interacting (DUI) mode. Based on these innovation modes, Binz and Truffer (2017) develop four stereotypical global innovation systems that differ in terms of their described dimensions. The structure proposed by Binz and Truffer (2017) is very useful to characterize the geographical dimension of different TIS. However, they do not account for how different degrees of local context dependency influence the development dynamics and performance of TIS functions. The first part of this thesis aims to start filling this gap by introducing and elaborating on the notion of configurational innovation systems and its counterpart, the generic innovation system.

The distinction between configurational innovation systems and generic innovation systems builds on the system proposed by Fleck (1993) for distinguishing between configurational and generic technologies. Fleck wanted a better understanding of "extremely complex and large-scale operating systems" (Fleck, 1993, p. 17) and consequently acquired expertise in how to "design, manage, and, above all, understand the development of such operating systems and the technologies involved" (Fleck, 1993, p. 17). According to Fleck, configurational technologies have a high level of context dependence, while generic technologies feature a low level of context dependence. The differing levels of context dependence have implications for the characteristics of the different types of technologies. For example, while configurational technologies do not have "explicit system standards specifying functions and performance" (Fleck, 1993, pp. 17–18), generic technologies do. Another example is that "information about the user requirements and the local conditions of operation is absolutely necessary" to implement configurational technologies successfully, due to their strong dependence on local contingencies, since the "specificity and uniqueness of the configuration stems from those requirements" (Fleck, 1993, p. 18). By contrast, in the case of generic technologies, once a dominant design has been found, information about user requirements and local conditions become of minor importance.

The proposition in this thesis is that the differentiation between technologies that are strongly influenced by local contingencies and technologies that are hardly influenced by local contingencies has repercussions on the respective innovation system dynamics and hence on the overall innovation system transition. This proposition is elaborated in Chapter 2 and Chapter 3 by describing how configurational and generic technological innovation systems differ and what effect this has on the pace of innovation system development.

1.6 Understanding coordination in configurational innovation systems

Given the local context dependence in configurational innovation systems, the dynamics in such systems are likely to be very different from those in generic innovation systems. Due to the different dynamics, the environment in which agents operate is likely to be different too. From a scholarly point of view, it warrants developing an understanding of how agents actually operate in such environments. Accordingly, while the first part of the thesis focuses on understanding configurational innovation systems by taking a systemic perspective, the second part places actors center stage and focuses on their agency in configurational innovation systems.

Agency can be understood as the “temporally embedded process of social engagement, informed by the past (in its habitual aspect), but also oriented toward the future (as a capacity to imagine alternative possibilities) and toward the present (as a capacity to contextualize past habits and future projects within the contingencies of the moment)” (Emirbayer and Mische, 1998, p. 963). While actors are influenced by the structures they operate within, they also shape structures through reproduction in practice (Geels and Schot, 2007b; Giddens, 1984, p. 2; Wittmayer et al., 2017). Hence, by using their agency, actors have the power to influence systems and accelerate the transition of socio- technical systems.

Both the MLP and the TIS concepts function as meso-level frameworks and have been criticized for their lack of agency (Genus and Coles, 2008; Kern, 2015; Lawhon and Murphy, 2012; Shove and Walker, 2007; Smith et al., 2005; Smith, 2010; Smith et al., 2010). While authors have substantiated the role of agency in these frameworks (Geels, 2011; Markard, Hekkert, Jacobsson, 2015), agency as a means to accelerate sustainability transitions is a subfield of transitions research that has not yet been sufficiently addressed.

As a first step towards a better understanding of agency, transition researchers have seemingly invested considerable efforts to understand actors and their roles. As a result, a substantial body of knowledge has emerged about specific actor groups, such as intermediaries (Kivimaa, 2014; Kivimaa et al., 2019; van Lente et al., 2003) and several actor typologies have been developed. For example, in a comprehensive review article on actors and agency in transitions research, Fischer and Newig (2016) identify four different typologies of group actors involved in transitions. The first typology differentiates actors according to the levels in MLP (niche actors, regime actors, landscape actors). The second typology differentiates actors according to their institutional domain (government, market and civil society). The third typology suggests differentiating actors according to governance levels (regional, national, global), and the fourth typology suggests differentiation according whether actors support or oppose a specific transition. A different attempt to typologize actors has been made by Avelino and Wittmayer (2016), who suggest analyzing actors as well as their power relations in transitions. Avelino and Wittmayer (2016) distinguish between four categories of actors (state, market, community, and third sector), and between actors at different levels of aggregation (individual actors, organizational actors, and sector-level actors).

While substantial efforts have been made to understand specific actor groups and how to categorize them, there is a lack of research on how agency actually plays out when it comes to system transformation and stimulating the diffusion of innovations. Although each actor decides when and how to make use of their agency, the coordination of many actors and their agency is required to influence the direction of a transition. As Smith et al. (2005, p. 1492) state, "system-level change is, by definition, enacted through the coordination and steering of many actors and resources." This highlights the fact that agency is strongly connected to coordination. Coordination can stimulate transitions in several ways. For example, it can foster transitions by implementing functioning governance systems (Ehnert et al., 2017; Fagerberg, 2018; Frantzeskaki et al., 2012; Grin, 2012; Loorbach, 2010; Meadowcroft, 2009; Smith et al., 2005), it can help to build powerful coalitions that promote and facilitate policy change (Haukkala, 2017; Markard, Suter, Ingold, 2015; Rennkamp et al., 2017), and it can create selection environments in which niche configurations can thrive (Reichardt et al., 2016). Although several contributions deal with topics connected to coordination (e.g., coalition building in transitions or the governance of transitions), there is a gap in the literature concerning what actually influences coordination and how it plays out. In addition to this gap, no attempt has been made to date to address how coordination plays out in systems that feature different levels of local context dependency. As the overall system dynamics are assumed to differ according to the level of local context dependency, it seems logical that the processes surrounding agency and coordination are also influenced by the level of local context dependency. In this respect, this thesis contributes by unpacking agency and coordination in systems that are highly dependent on the local context.

From a theoretical point of view, the structure of local context-dependent systems is likely to hamper expedient and efficient coordination for a variety of reasons. As an example, in local context-dependent systems, there are likely to be a greater number of involved actors than in less local context-dependent systems, since more specific technologies have emerged in the former to cater to the wider variety of application contexts. As a result, actors may not be aware of each other. For example, the number of heat technology manufacturers is likely to be higher due to the greater diversity of heating technologies. In addition to the higher number of manufacturers, the number of lobby groups is likely to be higher and therefore more difficult to manage. Furthermore, due to the higher number of technologies, heat technology related actor groups may be more diverse concerning their respective visions for the future. Hence, their actions are likely to be guided by differing interests and they may not necessarily be interested in joint coordinated activities. As a result, coordination is harder to initiate and to maintain. One possible outcome of the lack of coordination is that the policies implemented in such systems are likely to be rather fragmented.

While coordination is likely to be hampered in local context-dependent systems, meaningful coordination is likely to be the single most important lever to stimulate the development of configurational systems. This is because coordination can help stakeholders to agree on a shared vision of the future, which then allows them jointly to pursue institutional change that will accelerate the evolution of the system towards that vision.

Thus, in the second part of this thesis (Chapter 4 and Chapter 5) the focus is on coordination, in order to contribute to a better understanding of the process. Since coordination has not yet received much specific attention in the transitions literature, especially coordination in configurational systems, the first step is to analyze how coordination plays out in configurational TIS and what it is influenced by (Chapter 4). In this regard, the focus is on visions. The literature has shown that the alignment of visions plays a fundamental role in bringing actors together for joint actions (Kemp et al., 1998; Loorbach, 2010; Rohracher and Späth, 2014; Stirling, 2011). However, it has not been explored how the alignment of visions occurs in highly local context-dependent systems. Therefore, the main objective in Chapter 4 is to analyze how the similarities in visions regarding the desired end-states of sustainability transitions determine the coordination between actors supporting different emerging socio-technical configurations.

Since coordination is likely to be a strong lever to accelerate sustainability transitions, it is of additional interest to learn what actors can do to improve their coordination in order to exert greater influence on their institutional environment. In this regard, much can be learned from other areas of study that have accumulated substantial knowledge on coordination activities. Based on a review of an existing body of literature that addresses coordination, Chapter 5 elaborates on what determines the coordination of actors in political processes, and what can be learned for coalition building in transition contexts.

1.7 Research questions and outline

This thesis is structured in four content chapters (Chapters 2–5), each of which represents one study. At the time of writing, one of the four studies has already been published as a peer-reviewed paper in a journal, two have been submitted to a peer-reviewed journal, and another is ready to be submitted. An overview of the chapters is provided in Table 1.

Chapter 2 introduces and develops two contrasting types of TIS, namely the configurational innovation system and the generic innovation system. Based on the example of the German heating system and the German electricity system, the systematic differences between these types of TIS are described in a qualitative comparative study. The first research question is:

> *How do configurational and generic technological innovation systems differ, and what effect does this have on the pace of innovation system development?*

The comparative study of the heat and electricity systems in Germany is used to explain the rather slow development of the German heat TIS, which is related to the high level of local context dependency and the resulting higher degrees of fragmentation. The different levels of local context dependency have repercussions on the performance and development of technological innovation systems.

In Chapter 3, the thesis focuses on innovative district heating systems as a specific heat technology in order to gain a better understanding of how local contingencies influence the implementation of configurational technologies, and to derive suggestions for policymaking to stimulate the development of configurational TIS. District heating was chosen as the topic due to its specific configurational nature; implementing a district heating system is influenced by not only a number of technological but also social, local context contingencies. Chapter 3 aims to answer the following research question:

> *What local context-related factors influence the implementation of configurational technologies, and how can the development of configurational innovation systems be stimulated?*

Case studies of four district heating systems in Germany identified a number of local context-related factors that influenced the implementation of the networks. I argue that policymaking in configurational innovation systems needs to consider the specific attributes of such systems and aim at designing smart innovation system structures.

In Chapter 4 the focus shifts from analyses of systemic TIS to coordination. The chapter aims to explain the coordination and competition between actors in their efforts to shape the institutional environment in sustainability transitions. It sheds light on what determines the coordination of actors from different niches and therefore influences the emergence of strong coalitions in local context-dependent systems. More specifically, I propose that similarities of visions regarding the desired end-states substantially influence the actors' coordination-directed behavior. The research question posed is:

> *How do the similarities of visions regarding the desired end-states of sustainability transitions determine the coordination between actors supporting different emerging socio-technical configurations?*

To answer this question, an empirical study is made of networks between industry associations in the German heating system. I show that actors whose visions of future of socio-technical system developments overlap are more likely to coordinate their actions. Such visions are substantially influenced by the characteristics of the technologies promoted by their industry associations. Complementing studies presented earlier in this thesis, the data show that these actors' future visions are fragmented. This, in turn, is hampering the formation of a strong and coherent coalition for change.

Chapter 5 aims at a better understanding of the factors that influence coordination and draws implications for accelerating sustainability transitions. As shown in subchapter 1.5, the importance of coordination is emphasized across the transitions literature. However, the influencing factors that lead to successful coordination are not yet sufficiently understood. To complement the empirical account presented in Chapter 4, and to contribute to a better understanding of the factors that influence coordination in configurational TIS, and in transitions in general, Chapter 5 presents a literature review of the factors influencing coordination based on the Advocacy Coalition Framework (ACF). The ACF was chosen as it is a framework for understanding institutional change that puts actors and their agency center stage. The associated research question is:

> *What determines the coordination of actors in political processes, and what can be learned for coalition building in transition contexts?*

The results of the review show that even though there is some evidence that belief similarity as a key proposition of the ACF still holds, recent evidence suggests that its unique proposition is eroding and that coordination is influenced by a substantial number of other interconnected factors.

Finally, in Chapter 6, the findings from all four studies are summarized and overall conclusions drawn.

Table 1: Overview of thematic chapters

	Topic	Research question	Type of study	Case
Chapter 2	Strong local context dependency	How do configurational and generic technological innovation systems differ, and what effect does this have on the pace of innovation system development?	Empirical study (qualitative)	German heating system
Chapter 3	Strong local context dependency	What local context-related factors influence the implementation of configurational technologies, and how can the development of configurational innovation systems be stimulated?	Empirical study (qualitative)	German district heating
Chapter 4	Coordination	How do the similarities of visions regarding the desired end-states of sustainability transitions determine the coordination between actors supporting different emerging socio-technical configurations?	Empirical study (mixed methods)	German heating system
Chapter 5	Coordination	What determines the coordination of actors in political processes, and what can be learned for coalition building in transitions contexts?	Literature review	–

2 | Configurational innovation systems – explaining the slow German heat transition

Wesche, J. P., Negro, S. O., Dütschke E., Raven, R. P. J. M., and Hekkert, M.P. (2019) 'Configurational innovation systems – Explaining the slow German heat transition', *Energy Research & Social Science*, vol. 52, pp. 99–113.

2.1 Introduction

Recently, a debate has started in the literature on sustainability transitions concerning the pace of such transitions, and, if possible, how to accelerate them (Bromley, 2016; Fouquet, 2016; Grubler et al., 2016; Kern and Rogge, 2016; Smil, 2016; Sovacool, 2016; Sovacool and Geels, 2016). We welcome this discussion since the literature on sustainability transitions so far has under-conceptualized the dimensions that influence the pace of transition processes.

In this paper, we aim to contribute to this debate by highlighting specific characteristics of transition processes and their impact on the pace of transitions. Specifically, we propose that the local context dependence of technologies shapes and influences the functioning of technological innovation systems, and as a result, the pace of transitions.

Technological innovation systems (TIS) are socio-technical systems that enable the development and diffusion of innovations. They are usually considered to have four constituent pillars: actors, interactions, institutions and infrastructures (Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008b; Wieczorek and Hekkert, 2012). Their performance can be analyzed through so-called system functions (Hekkert, Suurs et al., 2007). Many studies have used the TIS framework to analyze emerging technologies to describe the key mechanisms that explain dynamics in innovation systems and their effect on technology development and diffusion (Bergek et al., 2015; Jacobsson et al., 2004; Kieft et al., 2016; Markard and Truffer, 2008b; Negro et al., 2007).

Recently authors started to differentiate between different types of TISs and suggest that the shape and behavior of TISs are influenced by the fundamental set up of the innovation systems. Differentiations have been made (1) in regard to types and number of sectors linked via the value chain of a TIS (Stephan et al., 2017), (2) the mode of valuation (Binz and Truffer, 2017; Huenteler, Schmidt et al., 2016) and (3) the mode of innovation and knowledge generation (Binz and Truffer, 2017). Especially Binz and Truffer call for a “greater emphasis on the role of multi-scalar networks and systematic differences between the innovation processes in various industries” (Binz and Truffer, 2017, p. 1284).

Regarding these differentiations we see two research needs. First, the differences exemplified so far have not yet been linked to the potential impact on TIS development speed and the pace of transitions in general. Second, while we highly value the recent developments regarding the Global Innovation Systems approach (Binz and Truffer, 2017, p. 1284) the speed of transitions may also be strongly impacted by local circumstances. We will analyze how different types of TISs interact with local contexts and how this influences the development speed of a TIS and how this in turn influences the speed of sustainability transitions.

Based on the earlier work of Fleck (Fleck, 1993, 1994), this paper proposes that it is possible to distinguish two kinds of TIS relevant to understanding transition speed: generic technological innovation systems and configurational technological innovation systems. In short, configurational innovation systems are strongly embedded in local contextual conditions, which results in substantial variety in their architecture between locations, whereas generic innovation systems are less dependent on local context and are prone to greater standardization across sites. This paper's initial hypothesis is that configurational innovation systems are hampered in their pace of development by their local context dependence and variability compared to generic and, hence, transitions involving configurational innovation systems are likely to take longer than those involving.

The research question of this paper is: How do configurational and generic technological innovation systems differ and what effect does this have on the pace of innovation system development? To address this questions, this paper compares the formative phases of the electricity and renewable heating TISs in Germany. The development of the renewable electricity TIS is far more advanced than the renewable heating TIS[1] resulting in high penetration of renewable electricity and low penetration of renewable heat technology. We will show that the renewable electricity TIS has many characteristics of a generic TIS, while the renewable heat TIS has many characteristics of a configurational TIS. Furthermore, we will show that this analytical distinction has substantial impacts on TIS functioning and build-up. For the

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[1] The electricity TIS can be broken down in innovation systems related to specific renewable energy technologies such as Solar PV and wind. Also, the heat TIS can be broken down in more specific technological innovation systems such as the heat pump innovation system or heat grid innovation system. In this article we will use the generic terms "electricity TIS" and "heat TIS" when we discuss characteristics that hold for most of the underlying innovation systems. Only when it is needed to highlight differences within the heat or electricity TIS we will specify concerning e.g., wind TIS or heat pump TIS.

empirical underpinning we have chosen to study energy transition developments in Germany since this country has demonstrated high renewable energy ambitions for a long time but has been successful only regarding renewable electricity. Our proposed framework may explain why this is the case.

This paper uses evidence from a single country case study. However, since the technologies utilized for energy transitions are very much the same across Central Europe, we deem this approach justifiable and helpful to understand the general influence of diverging local context dependence.

2.2 Conceptualizing generic and configurational TIS

Transitions studies and innovation systems

Socio-technical transitions are understood as far-reaching changes in the socio-technical structures and processes involved in the provision of particular societal functions, such as energy supply or mobility (Geels and Schot, 2010; Markard et al., 2012). Recently, much more attention has been paid to the temporality or pace of transitions (Bromley, 2016; Fouquet, 2016; Grubler et al., 2016; Kern and Rogge, 2016; Smil, 2016; Sovacool, 2016; Sovacool and Geels, 2016). This is a positive development since the ambitions set by the Paris Agreement require the energy transition to take place in a little more than three decades. This is a very ambitious time schedule.

The concept of innovation systems (Freeman, 1987, p. 5; Lundvall, 1990) may be useful in this debate since it provides a theoretical lens to study the rise of new socio-technical systems that offer alternative ways to fulfil societal functions.

Over the last three decades, different variations of innovation systems have been conceptualized and applied empirically. These include the concepts of national (Lundvall, 1995), regional (Cooke et al., 1997; Cooke, 2001), sectoral (Malerba, 2002), and technological (Carlsson and Stankiewicz, 1991) innovation systems.

The differences between these frameworks are obviously related to the system boundaries but also to “differences in each tradition’s epistemology, research objectives, and methodological approach" (Binz and Truffer, 2017, p. 1285). Where the national and regional systems of innovation frameworks are concerned with the overall innovative performance of countries and regions respectively, the technological and sectoral innovation systems frameworks are focused on the factors that explain the emergence and success of specific technologies and sectors. The TIS approach stands out due to its focus on understanding the key processes or system functions that impact the functioning of an innovation system.

The TIS framework focuses on the analysis of structural components: actors, interaction, institutions, and infrastructures (Carlsson and Stankiewicz, 1991; Hekkert, Suurs et al., 2007; Markard and Truffer, 2008b; Wieczorek and Hekkert, 2012). Actors are delineated into categories (individuals, organisations, and networks) based on their role in economic activity: civil society, government, non-governmental organizations (NGOs), companies, knowledge institutions, and other parties (Wieczorek and Hekkert, 2012, p. 76). Interactions can take place within networks or between individuals (Wieczorek and Hekkert, 2012, p. 77). Institutions can be divided into 'hard' institutions such as codified rules, legislation and standards and 'soft' institutions "which encompass a set of common habits, routines and shared concepts used by humans in repetitive situations" (Crawford and Ostrom, 1995; Wieczorek and Hekkert, 2012, p. 76). According to Wieczorek and Hekkert (2012), infrastructure encompasses three categories: physical, financial and knowledge (Wieczorek and Hekkert, 2012, p. 77). Physical infrastructure includes artefacts, instruments, machines, etc.; financial infrastructure comprises subsidies, financial programs, and grants; and knowledge infrastructure encompasses knowledge, expertise and strategic information (Wieczorek and Hekkert, 2012, p. 77).

The interesting contribution of the TIS literature compared to other innovation system frameworks is the understanding that different system structures may lead to comparable outcomes. For this reason, a structural analysis is complemented with a functional analysis in which the key processes that are relevant for good system functioning are analyzed (Table 2). "Since it is easier to judge or measure the quality of functions than the quality of structural elements, their addition has made the framework more practical for analysts" (Kieft et al., 2016, p. 33). System functions are not mutually independent but can reinforce or weaken each other. In the best case scenario, virtuous cycles are the result (Hekkert, Suurs et al., 2007, p. 426; Jacobsson and Lauber, 2006, p. 272; Suurs et al., 2010, p. 422).

Table 2: Description of seven key system functions

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 – and take advantage of – new business opportunities.
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 enable selection, which guides the distribution of resources.
F5	Market formation	This 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 in.
F6	Resource mobilization	The financial, human and physical resources are necessary basic inputs for all activities in the innovation system. Without these resources, other processes are hampered.
F7	Creation of legitimation	Innovation is by definition uncertain. A certain level of legitimacy is required for actors to commit to the new technology and invest therein, take adoption decisions etc.

Source: (Reichardt et al., 2016, p. 12) based on (Hekkert, Suurs et al., 2007).

Scholars studying the dynamics of innovation systems have discovered that distinct functional patterns occur at different stages of TIS development (Suurs et al., 2010). Therefore, it is important to identify the phase when comparing different innovation systems. In the TIS literature, two prominent phases are described: the formative phase and the diffusion phase or growth phase (Jacobsson and Bergek, 2004, p. 819; Negro et al., 2008; Suurs et al., 2010).

The formative phase is marked by many uncertainties (Bergek, Jacobsson, Sandén, 2008, p. 577) and “sets up the conditions for a technology to emerge and become established in the market” (Bento and Wilson, 2016, p. 95) see also (Wilson and Grubler, 2011). It is further characterized by “a range of competing designs, small markets, many entrants and high uncertainty in terms of technologies, markets and regulations” (Jacobsson and Bergek, 2004, p. 819; Negro et al., 2008, p. 926) as well as “by developments, such as actors being drawn in, networks being formed and institutions being designed that make the technology fit better to its surrounding structures” (Suurs et al., 2010, p. 420). The formative phase can be a very lengthy phase - easily two or three decades - (Bento and Wilson, 2016), and thereby slow down transition processes. Also, during the diffusion phase large differences in diffusion speeds are reported (Grubler et al., 2016; Smil, 2016).

So far, the majority of innovation system analyses have focused on scrutinizing the structural dimensions and system functions in order to find barriers, blocking mechanisms or systemic problems (see Bergek, Jacobsson, Sandén, 2008; Farla et al., 2010; Johnson and Jacobsson, 2001; Negro et al., 2012; Wieczorek and Hekkert, 2012). Up until now, not much conceptualization has been done to understand whether specific characterizations of a TIS impact the length of the formative and diffusion phase.

Factors that determine speed of TIS build up

Despite not many studies having made explicit how TIS characteristics impact development speed, some work has been done that is worth mentioning. Bergek et al. (2015) showed that a TIS is always embedded in context structures. Depending on the type of interaction with these context structures, TIS development may go faster or slower. However, this relation is not explicated. Simultaneous to the expansion of the analytical framework with broader context dimensions, recent work on technological innovation systems suggests that TIS are not genuinely similar but are shaped differently and therefore behave and develop differently. So far differentiations have been made first, in regard to types and number of sectors linked via the value chain of a TIS (Stephan et al., 2017) and second, the type of innovation and knowledge generation processes (Binz and Truffer, 2017; Huenteler, Schmidt et al., 2016).

Regarding the types and number of sectors linked via the value chain Stephan et al. (2017, 709) find, based on a quantitative analysis of patent data for lithium-ion batteries in Japan (1985–2005), that different sectors that form part of a TIS "vary in importance for knowledge development and diffusion". A generic categorization of TIS and how this may relate to development speed is however not provided.

With regard to the mode of learning and innovation (Huenteler, Schmidt et al., 2016) show that different types of product characteristics impact the evolution of knowledge generation in a TIS. While this is a significant contribution to better understanding TIS dynamics, no claim is made regarding impact on TIS development speed. Binz and Truffer (2017) highlight the importance of different type of learning and distinguish a Science, Technology and Innovation mode and a Doing, Using and Interaction mode. Based on these innovation modes, they develop four stereotypical types of global innovation systems that differ in the dimensions described (1. "Footloose GIS", 2. "Market-anchored GIS"; 3. "Spatially sticky GIS"; 4. "Production-anchored GIS"). The suggested structure by Binz and Truffer (2017) is very helpful for characterizing the geographical dimension of different TISs. In this case, no connection is made to the speed of TIS development either.

Generic and configurational technologies

Since the existing TIS literature does not provide a useful characterization of TIS that can easily be connected to the speed of TIS development we draw on Fleck (1993) who differentiates technologies based on different degrees of local context dependence. Generic technologies feature a low level of context dependence, while configurational technologies have a high level of context dependence. Since technologies are developed and diffused in the context of a TIS we expect that Fleck's differentiation for technologies may also prove to be a worthwhile TIS differentiation that may explain TIS development speed.

Fleck (1993) distinguishes between generic and configurational technologies by applying five dimensions which we expand via other literature in the following (for overview see Table 3):

1. Technological identity
2. Systematicity
3. System development dynamic
4. Flow of information
5. Innovation pattern

1. Technological identity is understood by Fleck as the “existence of explicit system standards specifying functions and performance” of a technology (Fleck, 1993, pp. 17–18). It reflects what Clark (1985), Huenteler, Ossenbrink et al. (2016), and Baldwin et al. (2014) among others call product architecture. Generic technologies have a more pertinent technological identity/product architecture than configurational technologies. For example, cars normally have four wheels, are powered by internal combustion engines and are built to transport a small number of persons from A to B in a certain time (see Oxford dictionary “car”)[2]. These attributes are only altered in very rare cases and thus constitute the strong identity that cars possess. Configurational technologies are unlikely to feature such explicit standards regarding function and performance, since they need to be reconfigured in each deployment setting. They exhibit a rather weak technological identity. Smart homes, for example, exhibit a very weak technological identity, since each project has its very own distinctive components architecture.

2. Technological systematicity is understood as the “existence of standard plans (...), and the provision of standard parts to realize the plans” (Fleck, 1993, p. 18). Since generic technologies are independent of the direct local technological context, it is easier for the respective original equipment manufacturers[3] (OEM) to work towards dominant designs and standardized plans (Murmann and Frenken, 2006). Fleck calls this process crystallization. Configurational technologies, on the other hand, are unlikely to shape such clear crystallizations since “local contingencies continue to resist stabilization or crystallization” (Fleck, 1993, p. 29). Purely configurational technologies need to adapt their components architecture (Henderson and Clark, 1990) to the local contingencies. While generic technologies can reach a dominant

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[2] It is acknowledged that cars also need their specific infrastructure. However, because individual cars can be directly and easily exchanged, they remain a generic technology.

[3] In this paper, we define an original equipment manufacturer as an enterprise that purchases components from a range of suppliers, compiles them into working systems and sells these under its own brand name.

design on a system level by crystallizing a specific component architecture due to the existence of standard plans (Fleck, 1993, pp. 28–29). Configurational technologies can only reach dominant designs on the component level (Peine, 2009, p. 406).

3. Generic and configurational technologies are thought to follow distinct product architecture dynamics. Due to their clearer technological identity and systematicity, generic technologies are likely to crystallize faster into dominant designs and thus follow "clear trajectories of development" (Fleck, 1993, p. 18). This is in line with Lee and Berente (2013) who show that once a dominant design is found, the patenting activities outside the core component increases. These clear trajectories allow for efficient generation and channeling of research funds and diffusion support, which again lead to ever-increasing system performances and cumulative causation (virtuous cycles). Since configurational technologies often lack clear identities and systematicities, they may also often lack clear development trajectories.

4. For generic technologies, once a dominant design is found, information about user requirements and the local conditions are of minor importance. Conversely, in order to implement a configurational technology, "information about the user requirements and the local conditions of operation is absolutely necessary" since the "specificity and uniqueness of the configuration stems from those requirements" (Fleck, 1993, p. 19; Vries et al., 2016, p. 53). This leads to different types of information flows. Since only negligible knowledge of local contingencies is required to advance generic products, the flow of information is mainly limited to the producer organizations. This organizationally restricted information flow also leads to centralized knowledge accumulation and learning processes. For configurational technologies, the flow of information is much less restricted and more diverse. It includes a variety of different component production organizations, intermediaries, and local implementing actors.

5. Generic technologies tend to follow innovation patterns where technological innovation and diffusion are independent of each other (Fleck, 1993, pp. 28–29). Technological innovation takes place in the manufacturing organizations, while diffusion takes place in the market. The case is different for configurational technologies. Since the information flow, knowledge generation and learning are so much more decentralized, innovation and diffusion cannot be abstracted from each other as they occur in parallel. Significant novelties may not only be

generated within the producer organizations but "may emerge at each instance of diffusion of the technology, and will tend to involve a number of different agents, users as well as suppliers" (Fleck, 1993, p. 28). Fleck describes this phenomenon as 'innofusion', since "process(es) of innovation and diffusion are collapsed together" (Fleck, 1993, p. 28).

Based on this representation generic technologies can be defined as technologies that are characterized by a strong technological identity, clear systematicity, and system development trajectories. They feature a rather one-directional information flow, centralized knowledge generation and learning. With generic technologies, the processes of innovation and diffusion take place independently.

Conversely, configurational technologies are defined as technologies that are characterized by a weak technological identity, adaptive systematicity and unclear system development trajectories. They feature multidirectional information flows, decentralized knowledge generation and learning. With configurational technologies, the process of innovation and diffusion are intertwined. Thus, their mode of evolution follows an innofusion pattern.

In the early phases of development before dominant designs are established also generic technologies struggle with technological identity since the search process is still in full swing. Later technological identities take shape and dominant designs emerge. For configurational technologies, this is much less the case due to the continuous adaptation of the technology to the setting in which it is implemented.

Building on these elaborations we define generic TIS as TIS that evolve around generic technologies. Additionally, we define configurational TIS as TIS that evolve around configurational technologies.

Fleck (1993) has provided an excellent framework to differentiate technologies. The key issue in this paper is to understand how this differentiation affects the energy transition in Germany and more broadly the pace of technological change in general. To understand this, it is necessary to apply the framework provided by Fleck (1993) to the TIS framework. We expect that innovation systems that form around configurational technologies will develop according to different pathways than a TIS forming around generic technologies due to different context interactions. In that regard, we follow up the work of Bergek et al. (2015) who indicated relevant context structures for a technological innovation system but did not explicate how interaction of context structures on the TIS influence dynamics and development speed. Furthermore, we follow up on Huenteler, Schmidt et al. (2016). Their differentiation between mass-produced products and complex products is helpful to understand different models of innovations but configurational technologies differ from complex products since for configurational technologies the architecture differs depending on the implementation context while for complex products the architecture is roughly stable. Furthermore, our approach adds to Binz and Truffer (2017). They make a distinction between standardized versus customized products. The latter are dependent on a Doing, Using and Interaction mode of innovation that is specific for different territorial contexts. At first glance this seems to match the definition of configurational innovation system but in their definition customized products do not need to be adapted to different implementation settings. Furthermore, their differentiation between customized and standardized valuation does also not explicitly cater to explain innovation system acceleration. Furthermore, they define innovation subsystems as their unit of analysis. The boundaries of these subsystems “can correspond to national or regional borders, but they may as well develop in networks that transcend national and regional borders” (Binz and Truffer, 2017, p. 1287). Hence, their conceptionalization operates on multi-scalar levels, but do not take into account the physical local context as is the case for configurational innovations.

In the following sections we apply the framework to the cases of German renewable electricity and heat. While doing so, it is to be acknowledged that all technologies in the electricity-heat realm feature different levels of local context dependency (Figure 6). Therefore, the goal of this paper is not to offer a full-fledged analysis of all heat and electricity related technologies but highlight general patterns and extremes. The focus of this paper is to assess the impact of technology characteristics on innovation system functioning, which has not been done before, as highlighted in section 2.2.

We want to emphasize, that this paper generally adopts a socio-technical and co- evolutionary research approach. Our starting point is that the way how technological innovation systems emerge is the outcome of an alignment process between technological and social developments (and between TIS and context) (Bijker, 1999), rather than determined by technological characteristics. We do not, however, assume that TIS takes technology as an entrance point for analysis. Nevertheless, we have thoroughly reviewed the paper to make sure the socio-technical perspective is reflected throughout.

Table 3: Theoretically-derived characteristics of generic and configurational technologies adopted from Fleck (1993)

	Generic technologies	**Configurational technologies**
Technological identity	Strong technological identity due to generic character.	Weak technological identity due to ever-changing local contingencies.
Systematicity	Clear systematicity concerning standard plans and parts due to dominant design.	Adaptive systematicity concerning standard plans and parts, needs to be continuously redefined due to ever-changing product architecture.
System development dynamics	Clear system development trajectories due to dominant designs.	Rather unclear system development trajectories due to lack of dominant designs.
Flow of information	Mainly within producer organizations and one- directional towards downstream actors. Centralized knowledge generation and learning.	Multidirectional large and diverse information flow. Decentralized knowledge generation and learning.
Innovation pattern	Independent innovation and diffusion, which lead to Darwinian evolutionary interactions.	Innofusion due to intertwining of innovation and diffusion and need for high component adaptability.

2.3 Methods

To validate the distinction between generic and configurational innovation systems, we compare the renewable electricity TIS that evolve around onshore wind and solar PV (generic technologies) and renewable heat TIS (configurational technologies) in Germany, focusing on their formative phases. These formative phases differ in timing. The formative phase of onshore wind and solar PV ended roughly around the early 2000s while the renewable heat TIS still finds itself in the formative phase. The dynamics of onshore wind and solar PV are well documented and our analysis thereof is based on the following secondary data: Jacobsson and Johnson, 2000; Jacobsson et al., 2004; Jacobsson and Bergek, 2004 Dewald and Fromhold-

Eisebith, 2015; Dewald and Truffer, 2011, 2012; Geels et al., 2016; Jacobsson and Lauber, 2006; Lauber and Jacobsson, 2016; Lauber and Metz, 2004. Even though each of the papers focuses on one specific technology and different time periods, the reported dynamics could well be related to the concept of a generic TIS. The literature collection on the formative phase of the onshore wind and solar PV TIS in the renewable electricity TIS was conducted via SCOPUS using the following key words: "German*," "electric," "innovation," "system," "transition," "onshore wind," "solar PV." These were combined into search strings using the "AND" operator. These were limited to the subject areas of "energy," "environmental science," "social science," "multidisciplinary," and "business, management & accounting." This search was expanded via a snowballing procedure using the literature list of the collected contributions to gather additional sources. For insights into TIS functions, the following key terms were additionally used for the paper search: "entrepreneurial activities," "knowledge development," "knowledge diffusion," "guidance of search," "market formation," "resources mobilization," "legitimacy," "legitimation," and "positive externalities."

Due to the lack of heat-specific research contributions, the analysis here is based on original primary and secondary data. 37 semi-structured interviews were conducted with experts who have been involved in implementing low-carbon residential heating projects, i.e. project developers, company and industry representatives, local and regional politicians and representatives of utilities and communities (see Table 12 in Appendix A). The experts were selected to cover different levels of the heat TIS, such as local and national, and the great majority of actors in the innovation system (Kuhlmann and Arnold, 2001).

The interviews were divided into several topics: First, the interviewees were asked about the drivers and barriers to transition; then they were asked about future scenarios, and finally what should be done to improve the situation/recommendations. Local actors were questioned in more detail about their specific projects, while the questions for national level actors focused more on the national level.

All the interviews were fully transcribed and labelled with MAXQDA using categories derived from Table 2 and Table 3. In order to reach inter-coder reliability, the interviews were coded independently by both the first author and the second author. Any differences in the coding results were analyzed and refined. Where possible, insights from primary sources were compared with secondary sources such as documents from ministries and other organizations, interest groups and research reports to reduce interpretation bias.

2.4 Comparing the pace of TIS development: electricity and heating

The following section introduces the electricity and the renewable heating TISs in Germany and then compares them along their structural dimensions and system functions.

The onshore wind and solar PV TIS and renewable heating TIS in Germany

The pace of transition towards decarbonization diverges substantially in the electricity and heat sectors in Germany. In both sectors, demand has been quite stable and reductions due to efficiency have been rather meagre. However, the share of renewable energy in the electricity sector started growing at the beginning of the 1990s and has experienced high growth rates since the start of the diffusion phase in the early 2000s (Figure 2, line 1 - grey).

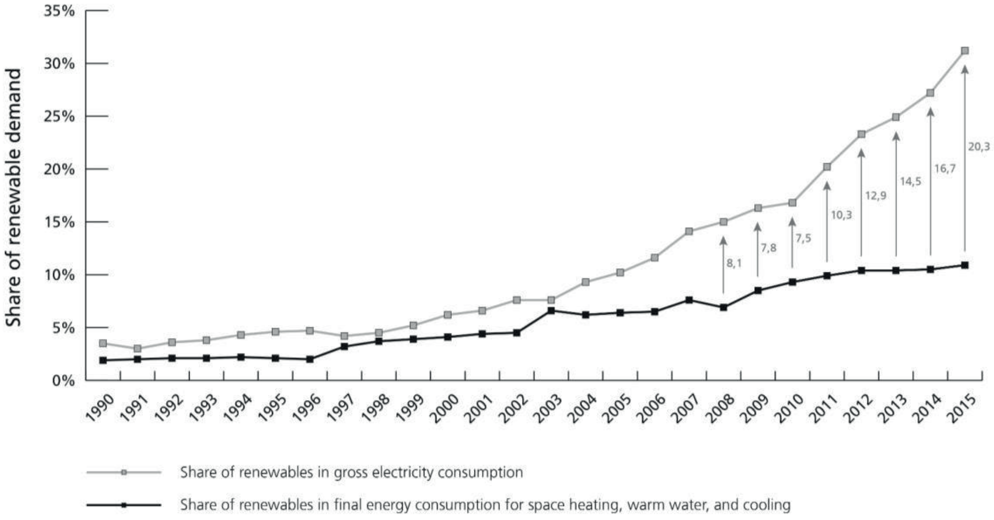

Figure 2: Shares of renewable energy in gross electricity consumption and share of renewables in final energy consumption for space heating and warm water heating (and cooling) (AGEE-Stat, 2020)

The development in the heating sector lags behind (line 2 - black). At the beginning of the 1990s, the share of heat provided by renewable sources was at a similarly low level as in the electricity sector. Over the last 25 years, the share from renewable sources in the heat sector has grown, but only at a slow pace.[4] Since the beginning of the 2000s, the renewable shares of the electricity and heating sectors have increasingly drifted apart.

Electricity – onshore wind and solar PV as generic TIS

Onshore wind and solar PV TISs were the technologies that substantially propelled the German electricity transition forward. For this reason, we will focus on these in the following segment. They are generic in character concerning their supply and demand side. On the demand side they are generic, because electrons are all equal. It does not matter which technology was used to generate their movement. On the supply side they feature generic characteristics that developed over a period of experimentation in the 1970s and 1980s (AGEE-Stat, 2020, p. 6). Other technologies are not included because their growth potential is limited (hydro), they only had a short peak due to increase of financial support but are very debated regarding further deployment (biogas) or their costs continue to be exceptionally high (e.g., tidal). Onshore wind and solar PV developed clear technological identities with clear systematicities during the 1990s (Cherp et al., 2017; Dewald and Truffer, 2011; Joas et al., 2016; Johnson and Jacobsson, 2003; Lauber and Metz, 2004). For example, by the 1990s, the horizontal-axis three-bladed design in the wind industry and Multi-Si and Mono-Si in the solar PV industry had developed into the dominant designs (Johnson and Jacobsson, 2003, p. 203). Since then, the wind turbines and solar cells their system development trajectories have become clear, focusing on conversion efficiency gains and lower production prices.

Once dominant designs emerged, original equipment manufacturers of these technologies did not need to focus too closely on the local context anymore because deployment is relatively independent of local circumstances since the generated electricity is a generic good which in the vast majority of cases is transported away via the local electricity grid. The designs of wind turbines and solar panels are not adapted to specific local circumstances. They are mass produced following an engineering logic that optimizes energy yields at the lowest costs. Therefore, most knowledge generation takes place upstream and communication is rather one-directional,

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[4] This low pace again needs to be viewed with caution since it includes a 2.5 fold increase of biogenic solid fuels (mostly firewood) which cannot be increased indefinitely due to resource scarcity and other environmental problems, such as the increased output of particulate matter and other harmful substances (Umweltbundesamt (2017).

flowing from upstream to downstream (Dewald and Truffer, 2011; Marinova and Balaguer, 2009, p. 463). For instance, because PV panels are produced in series and can be implemented as an add-on technology, there is no real need for bi-directional communication flows. Since there is no need for extensive feedback from downstream diffusion and implementation to upstream innovation and development, the onshore wind and solar PV TISs feature rather independent innovation and diffusion patterns[5].

Heating – A configurational TIS

The heating sector in Germany is configurational on the supply and the demand side. Since heat cannot be transported efficiently over longer distances, the heating generation capacity needs to be deployed very close to its point of use[6] and needs to cater to the demand of each building. Since buildings differ in size, age and purpose, the heating systems for each of the more than 20 million residential and non-residential buildings in Germany (Bundesinstitut für Bau-, Stadt-, und Raumforschung, 2016, p. 3; Statistisches Bundesamt, p. 16) need to be tailored to the building's characteristics. To cater to these diverging needs, a broad range of technologies has been developed on the supply side:

Single-building solutions based on pellets, biogas, solar thermal appliances as well as different heat pump systems such as air source heat, ground or water-based systems, in combination with or without solar PV.

Multi-building heat networks, which can be based on heat from geothermal, waste, biogas or biomass, solar thermal, or large-scale heat pumps. Depending on the buildings' characteristics, these can run at high temperatures for existing buildings or low temperatures for newly constructed buildings.

Each heating system therefore represents a unique case, therefore it is not surprising that clear technological identities have not (yet) emerged. Dominant designs only arose at the component level such as heat pumps, solar thermal appliances, pipes and heat exchangers that now

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[5] We only focus on standardized PV panels and exclude building integrated PV. The latter is a configurational technology since the design of the panels strongly depend on the characteristics of building facades.

[6] This paper only looks at space heating and warm water production for residential, commerce, trade and services use. Industrial heat is excluded.

build on decades of efficiency gains. Since the combination of components in the heat TIS varies depending on the local physical conditions and social preferences, specific repeatable combinations are rarely obvious and the systematicity of applications needs to be continuously adapted and redefined. Due to this continuous adaptation, substantial parts of the cost are attributed to manual labor which in turn represent cost components that cannot be reduced in order to lead to overall cheaper products. As an example, cost reductions for solar thermal heat systems have only been marginal since the turn of the century and experts do not see great potential without major technology breakthroughs (Wenzel et al., 2015, p. 127). For heat in general, a few crystallization approaches are on the horizon such as the passive house standard for existing buildings or highly efficient prefabricated buildings. However, clear development trajectories are still mostly absent. Information flows are multidirectional and diverse due to the huge number of locally operating installers and their ramified interaction with guilds, energy agencies, component manufacturers, technology representatives and policy-makers. Since information is multidirectional and knowledge generation and learning are decentralized, innovation efforts and diffusion are strongly intertwined; in fact, an “innofusion” pattern is emerging as introduced by Fleck.

Identification of the formative phases

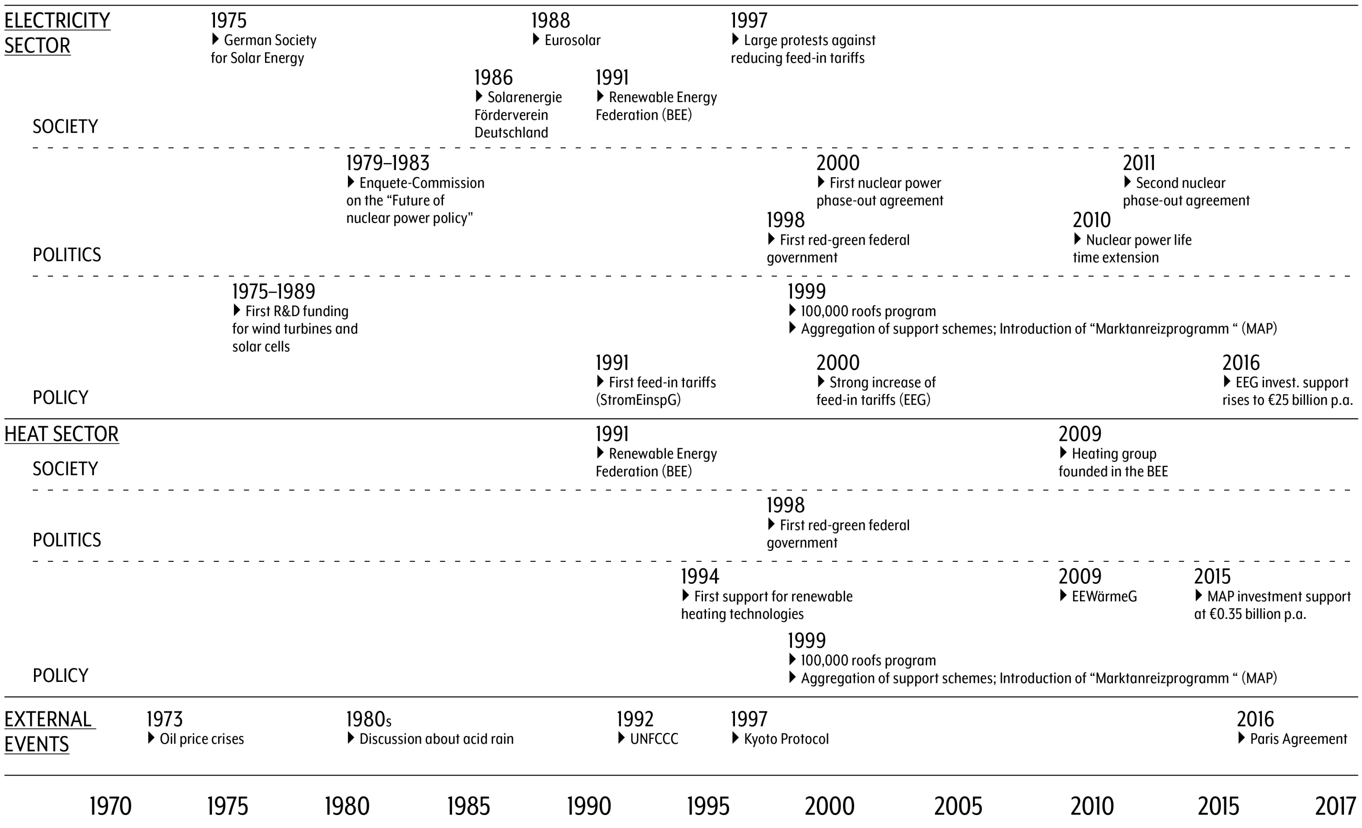
In the previous section, we argued that the onshore wind and solar PV TIS has a generic character, while the renewable TIS in the heating sector has a configurational character. Since we now know that the pace of development in each TIS diverges substantially, we will now study whether the type of TIS affects its dynamics by comparing the developments in the two TISs. For reasons of better comparability, we select the formative phase in each TIS.

As displayed in Figure 3, the developments of the two TISs took place in clearly distinct time periods. The development of the renewable onshore wind and solar PV TIS can be traced to the aftermath of the oil crises in the 1970s (Jacobsson and Lauber, 2006, p. 263). After a long-fought battle for legitimacy that was often conducted by community initiatives (Dewald and Truffer, 2011; Jacobsson and Lauber, 2006), the implementation of the Renewable Energy Sources Act in 2000 marked the final milestone needed for renewable electricity technologies moving from the formative to the diffusion phase. In this paper, we suggest that the diffusion or growth phase for onshore wind and solar PV started around the year 2000. This is roughly in line with Bento & Wilson 2016, p. 102) and Dewald and Fromhold-Eisebith (2015, p. 117).

Bento and Wilson (2016, p. 102) suggest that the formative phase ends when 2,5% of the market potential has been reached. This was the case for onshore wind in 1999 and Solar PV in 2002. Dewald and Fromhold-Eisebith (2015, p. 117) specifically suggest 2004 as the year the transitions happened for Solar PV. We do acknowledge that pinpointing a specific year is a somewhat delicate due to different definitions of the formative phase.

Like the renewable electricity TIS, some renewable heating technologies, such as the heat pump, can also be traced back for several decades. Despite this, the renewable heating TIS still finds itself in the formative phase for the following two reasons: (1) Up until now, there have only been incremental increases in the share of renewable technology in the German heating TIS when biomass is excluded (Figure 2); (2) the institutional alignment for accelerated growth has not yet happened: Fossil fuel technologies are still dominantly widespread and the subsidy structure lags far behind the financial support available for electricity technologies in the 2000s. For this reason we suggest that the heating TIS did not make the leap from the formative to the diffusion phase (yet).

Figure 3: Timelines of the electricity and heat transition in Germany



Comparison of the heat and electricity TIS in Germany

After defining the time frame in which the electricity and heat TISs are to be compared, we examine how they differ with regard to system development. We start by comparing the structural dimensions of technological innovation systems and continue with the functions suggested by (Hekkert, Suurs et al., 2007). While doing so, we acknowledge that not all electricity technologies are of generic character and all heat technologies are exclusively configurational. Instead we suggest that the level of context dependence differs among the elaborated technologies (Figure 6) and there are also electricity technologies that are more context dependent, such as specific wind farm types (wind offshore, high altitude farms). However, in our text we will focus on onshore wind and solar PV and we will show that these electricity technologies that propelled the German electricity transition forward in general are on the generic side of the spectrum, while the utilized heat technologies are on the configurational side of the spectrum.

Structural comparison

Actors

On the supply side, the actor structure in the renewable TIS is more compact and less fragmented than the actor structure in the heat TIS. For wind onshore farms and roof- top PV, components are integrated upstream by the original equipment manufacturers (OEMs) who rely on a lean downstream project development and electricity sales structure (Figure 4).

In contrast, the actors in the renewable heating TIS do not revolve around upstream OEMs. In most cases, local installers integrate the locally suitable components into functioning configurations (Figure 5). These local installers are often small firms. Furthermore, many installers not only install heating systems, but also often create and install kitchens and bathrooms. Thus, as the businesses are small and less specialized, their level of expertise tends to be smaller than project developers in the electricity sector Due to the large effort required to configure these locally contingent systems, the capacity of these local installers is often limited to a small number of installed heating systems per year. This leads to an immense number of firms that operate in clearly demarcated geographical territories.

This is clearly demonstrated by the 50,000 mostly small companies that are registered by the German Sanitation, Heating and Air Conditioning Installers Association (ZVSHK). This association represents all three types of businesses since these small companies often operate in more than one of these fields.

A representative of a renewable energy association stated:

> *"Yes, the situation in the heating market is extremely heterogeneous overall and that is one of the reasons why this heating market is not really accelerating."*
> (Interviewee #31)

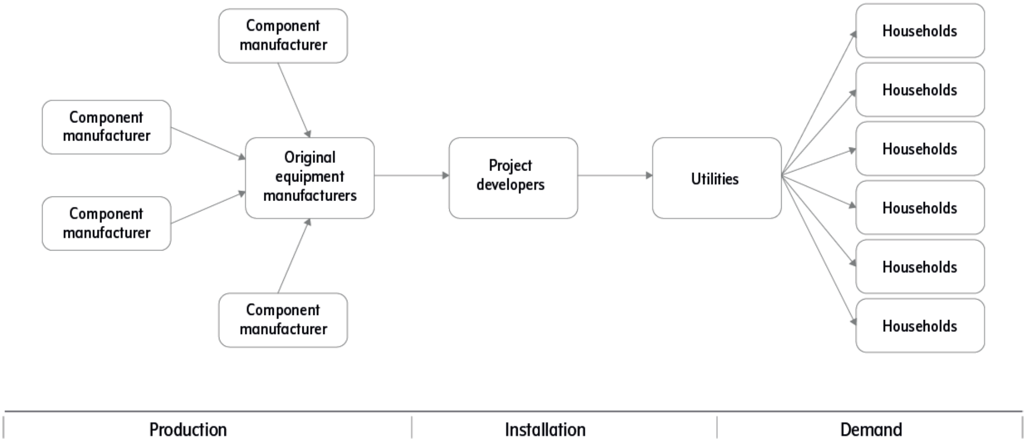


Figure 4: Structure of core actors for generic technologies such as onshore wind farms and (partly) roof top solar PV.

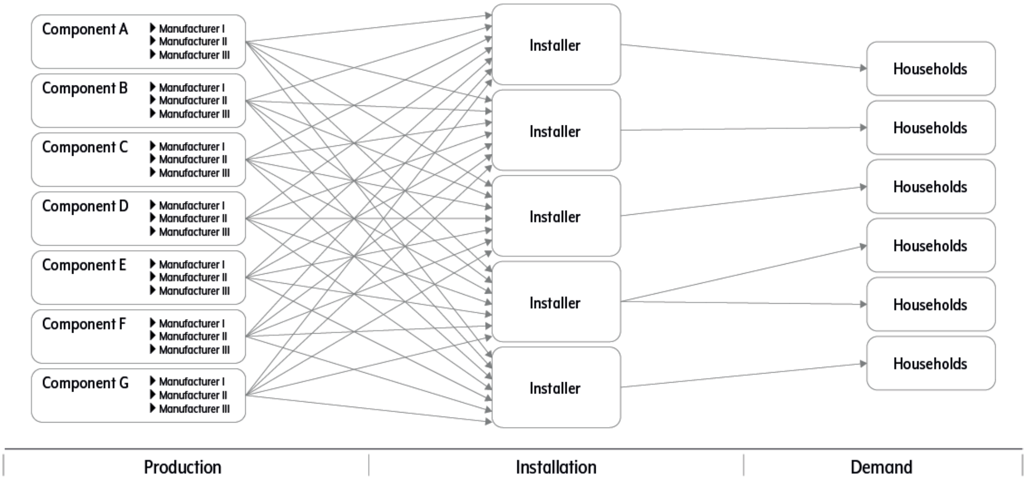


Figure 5: Structure of core actors for context dependent technologies such as single house heating solutions or heat grids, but also special types of wind farms (low-speed or high-altitude wind farms).

On the demand side, the role of users is much more pronounced in the heat TIS than for the electricity TIS analyzed. When a household aims to change its electricity supply, profound changes only seldom need to be performed around the house. Even when solar panels are installed the effort remains limited. In contrast, when the heat supply is to be changed, the effort is much larger, since new pipes may have to be installed, the garden is dug up for the connection to a heat grid or the house needs to be fully energetically refurbished so that for instance a heat pump suffices. For some heat technologies the role of users is even more essential. For instance, heat grids only get realized when a substantial number of households unanimously agree to buy into the project.

Interaction

Interaction and network-building among onshore wind and roof top solar PV in the electricity sector was more pronounced early on than in the renewable heat TIS. This is in contrast with the heating sector, where the actors have not yet managed to form strong and powerful network structures that channel interaction.

Network-building for onshore wind and solar PV started in the 1970s. In the 1970s and 1980s, network-building fostering interaction took place on two levels. On the local level, a number of citizen-led initiatives were founded to promote solar PV on the ground with the support of solar activists and local utilities (Dewald and Truffer, 2011, p. 292; Jacobsson and Lauber, 2006, p. 272; Lauber and Metz, 2004, p. 605). On the national level, several more formalized networks were established to promote solar energy in Germany (Jacobsson et al., 2004, p. 14): International Solar Energy Society, German Section (1975)[7], German Solar Association[8] (1987), and the German Association for the Promotion of Solar Power[9] (1986). Furthermore, the German Renewable Energy Federation (BEE) was founded in 1991 to better represent their political interests and, in 1996, key industrial players also founded the German Wind Energy Association (BWE). These initiatives and networks facilitated the interaction and coordination among actors advocating renewable electricity technologies.

On the national level in the heat sector network-building also started with the foundation of the International Solar Energy Society – German Section in 1975. However, due to the dispersed actor structure and strong local focus, it was continuously hampered, and actors did not manage to build up strong political momentum. At the project implementation level, the large number of installers and project developers operate in clearly demarcated geographical territories. This has led to a low level of mutual awareness, resulting in fuzzy networks. The actors at the component manufacturing level are divided into a group of incumbent producers who are expanding their product portfolio with more renewable products, and new entrepreneurs entering the market. Due to this void between incumbents and new entrants, there has been little network- building regarding the technologies in question. Incumbents remain in their existing networks and new actors are at best organized in very specific interest groups. The only platform on renewable heat technologies that brings most of the component manufacturers and specific technology lobby groups together is the heating working group of the *German Renewable Energy Federation* (BEE)[10]

Institutions

As with most inventions, early formal institutions within the electricity and the heat TIS were not favorable. Despite this, the actors in the onshore wind and solar PV TIS managed

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[7] http://www.dgs.de/dgs/

[8] https://www.solarwirtschaft.de/en/about-us.html

[9] http://www.sfv.de/

[10] From the beginning on the BEE advocated in favor of renewable heating technologies. However this specific working group was only established in 2009 Bundesverband Erneuerbare Energien e.V. (2012, p. 3).

to implement a continuous stream of new and ever growing support schemes (Figure 3) (Jacobsson and Bergek, 2004, p. 833); (Dewald and Truffer, 2012; Jacobsson et al., 2004, p. 17), which culminated eventually in the enactment of the German Renewable Energy Sources Act (EEG) (see Figure 3). The actors in the heat TIS were less successful. Even though the key financial support scheme, the Marktanreizprogramm (MAP) (Market Incentive Programme for Renewable Energies), its predecessors and surrounding schemes offered some incentives, the overall volume was not comparable to the financial support for the technologies in the renewable electricity TIS, which grew substantially once implemented. Total EEG-related remuneration started off with roughly 800 million euros in 2000 and reached about 10.5 billion euros in 2009 (Netztransparenz[11]). In comparison, the MAP never exceeded 430 million euros[12]. Furthermore, renewable heat technology providers continue to struggle with incoherent policies that also feature financial support schemes for fossil fuel-based heating appliances.

There is also a strong relation between technological characteristics and soft institutions. Solar PV as one of the renewable electricity technologies gives consumers the opportunity to display their environmental awareness. On the other hand, heating technologies in general do not seem to give consumers the opportunity to show their moral and normative alignment with environmental concerns and are often considered 'dirty' technologies.

An interviewed energy researcher stated:

> *"In the heating area, that is a bit more difficult (...) because you have to go into the basements. Its dirty there and untidy. This is a place where you basically do not want your neighbors to enter."*
> (Interviewee #29)

Furthermore, since it is harder to show societally accepted beliefs with systems that are woven into the physical structure of buildings, house owners and inhabitants are often reluctant to invest more time and money than is actually required and tend to replace components as and when needed rather than implement complete renovations, leading to prolonged refurbishment cycles. Apart from that, due to its customized configuration, heating infrastructure is expensive to retrofit and often loses out to kitchen and bathroom refurbishments.

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[11] https://www.netztransparenz.de/EEG/Jahresabrechnungen

[12] http://ee-waerme-info.i-ner.de/index.php?title=Marktanreizprogramm

The same expert stated:

> *"And once people invest, (...) they prefer to invest in garden design, new kitchens or new bathrooms (...). Investment opportunities such as heating are not prioritized, because the living comfort of the inhabitants is not directly increased (due to the same temperature reached)."* (Interviewee #29)

Physical and knowledge infrastructure

Physical infrastructure is highly relevant for both onshore wind and solar PV TISs and the renewable heat TIS. All technologies have to deal with existing infrastructure.

Since generation and consumption is decoupled in the electricity sector, physical infrastructure such as high voltage grids is important to bridge the generation-demand divide. For the development of the renewable heating TIS, physical infrastructure is similarly influential but there is a broader variety. On the one hand, the existence of infrastructure that supports fossil fuels such as gas pipelines creates local path dependencies incentivizing local consumers to stick to the current consumption patterns based on fossil fuel (in this case gas). On the other hand, already implemented renewably-based heating grids or heating grids in transformation can accelerate the local heat transition.

Typically, configurational technologies need to deal with large differences in local physical infrastructure or need to build a variety of new infrastructures, depending on the context. It is the variety in infrastructures that is a hampering factor for configurational technologies.

The knowledge infrastructure for onshore wind and solar PV TISs is rather centralized. Since onshore windfarms and solar energy systems are built in series, their development only needs to consider the local context to a limited degree. Therefore, a great deal of knowledge generation is likely to take place in the manufacturing organizations and remain there. In contrast, in the heat TIS, each installer or project developer is equipped with maximum component expertise and the knowledge how to interlink them - at best. However, due to the sheer number of installers, the provision of this knowledge is a huge task and currently not institutionalized very well.

Functional comparison

F1. Entrepreneurial activities

In the onshore wind and solar PV TISs, the core entrepreneurial activity of integrating components into running systems is done further upstream than in the renewable heating TIS because of the lower context dependency. When developing the onshore wind and solar PV TISs, limited groups of OEMs were supported by governmental support schemes. Since their products need less adaptation to the local context, they require fewer commercial and practice-oriented experiments, which leads to crystallizations and the rapid emergence of dominant designs. For instance, in 1993, only five OEMs covered about 70% of the German wind market (Allnoch, 1993). These then acted as a hub to help develop the horizontal-axis three-bladed construction type into a dominant design that was then offered in a limited number of sizes (cf. (Jacobsson and Lauber, 2006, p. 263). In contrast, in the more context-dependent heat TIS, the integration of components takes place substantially later downstream - specifically at the level of the buildings or neighborhoods to be equipped. The large variety of technological, institutional and infrastructure-related contingencies makes every case unique and requires a large number of local installers. Often installers are not available or are insufficiently trained.

A former head of a local energy agency stated:

> *"The installers were so busy here in the region that you had to be lucky just to get one."*
> (Interviewee #6)

Since the number of entrepreneurs is so large, buying power is very dispersed which allows a large number of suppliers to co-exist. For instance, in 2014, heat pumps from 100 different manufacturing companies were supported by the MAP (BMWi, 2016, p. 41). This low market concentration in the heat TIS leads to challenging component selection processes for local installers on the one hand and to disperse flows of investment in R&D on the other hand. All these factors pose barriers to the development of dominant designs likely to lead to a more efficient heat TIS that drives down costs.

F2. Knowledge development

Relevant learning processes take place upstream and downstream for onshore and solar PV TISs. Due to the generic character, downstream technologies more quickly converge to a dominant design than their upstream counterparts. Hence the remaining learning processes mainly relate to upstream component integration. Knowledge development is further fostered by the small number of dominant OEMs that are focused on a single product that they replicate continuously.

In contrast, in the heat TIS, a larger part of knowledge development takes place downstream at the point of deployment. Here, knowledge development is generally hampered since the learning-by-replication potential of local installers is limited because they are often very small companies that carry out only a limited number of applications per year. Furthermore, since the implementation of radically new heat configurations requires additional time and financial investments, these actors are often reluctant to move away from their conventional mostly fossil fuel-based solutions.

An energy researcher stated:

> *"If you look at them (the installers of conventional fossil fuel technologies), they find it easier (…) if you have an oil, - or a gas boiler or a burner that needs checking (or replacing)."*
> (Interviewee #29)

These factors together with the dispersed actor structure in the heat TIS and unclear guidance of search lead to complex decision-making with high levels of uncertainty for component manufacturers on how to allocate R&D spending and which specific technologies to invest in, in order to build up knowledge. One result of this is the limited amount of resources invested in optimizing the integration of products into working systems, which leads in turn to low levels of standardization.

F3. Knowledge diffusion

Most knowledge in the renewable electricity TIS is developed by OEMs and suppliers so it is codified, standardized and diffused by a limited number of homogenous actors. Their group structure simplifies the formation of networks, and the codified knowledge allows for straightforward knowledge diffusion that also integrates locally active intermediaries. For instance, solar PV as a standardized product was interlinked with an easy-to- understand EEG-based business model so that local initiatives could easily adopt it and disseminate it widely (Dewald and Truffer, 2011, p. 292, 2012, p. 408; Geels et al., 2016, p. 902); (Jacobsson and Lauber, 2006, p. 263). In contrast, in the heat TIS, a broader and fuzzier group of actors needs to diffuse a mix of internally analytical and only locally available synthetic knowledge (Moodysson et al., 2008). Standardized solutions are largely absent so that the multiplying effects achieved for solar PV have not been replicated in the German heat TIS. In addition, local energy agencies which can be understood as prime examples for diffusion-fostering intermediaries continue to often be absent and where they are operative they tend to focus on renewable electricity appliances. This illustrates the lack of well- institutionalized knowledge flow mechanisms in the heat TIS.

F4. Guidance of search

Since dominant designs were quick to emerge in the renewable onshore wind and solar PV electricity TISs, the focus of renewable electricity advocacy groups swiftly narrowed to wind, solar PV (and also biogas) (Jacobsson and Lauber, 2006, 260ff). These groups were able to convey a clear message based on the potential for emission reduction and energy generation expansion, which was easy for policy-makers to grasp. Policy has been contested at times, but the increasingly strong advocacy coalition in favor of renewable electricity deployment not only managed to keep public financial support in place, but on an upward trajectory. For instance, a government proposal "to reduce feed-in rates"(...) in 1997 "led to a massive demonstration bringing together metalworkers, farmer groups and church groups along with environmental, solar and wind associations" resulting in a withdrawal of the policy proposal (Jacobsson and Lauber, 2006, p. 265). The technological and actor variety in the heat TIS is greater than for onshore wind and solar PV. Therefore, policy-makers face higher technological complexity. Higher technological variety and complexity makes a clear vision on the part of technology actors even more important and urges technology actors to help government to construct such visions. However, the heat actors continue to fall short on constructing coherent policy expectations and policy suggestions due to too strong diversity in perspectives and potential development trajectories. For example, due to differences in opinion on which technology type to prefer (central - decentral, electricity vs. biomass) they seemingly have issues when trying to represent a coherent vision of a more decarbonized heating sector.

A manager at an integrated heat technology incumbent stated:

> *"Our solar thermal appliance unit sells solar thermal systems in combination with oil and gas heating systems. At the same time, we are demanding a stop to the production of oil and gas heating. So of course, there are inconsistencies".*
> (Interviewee #35)

So far, this shortcoming has meant there is no clear guidance of search that supports only renewable technologies. In fact, even though the German government has declared the goal of achieving a nearly climate-neutral state by 2050 (Bundesministerium für Wirtschaft und Energie, 2010, p. 22), it continues to incentivize fossil fuel-based heating appliances.

A representative of a renewable energy association stated:

> *"Today we still promote oil heating and gas heating systems through the KfW banking group. One can roughly calculate what is lost for climate protection if one does not use the opportunities to immediately switch to renewables."*
> (Interviewee #31)

Even though guidance of search may not be very clear for the renewable heat TIS, there is an array of support programs available offering investment support and soft loans. However, due to the complex structure and insufficient support per project, considerable sums of available funds are not drawn upon (BMWi, 2016, p. 41). Furthermore, the overall funds invested have not increased substantially over the years. For instance, the MAP has experienced quite strong fluctuations (between 229 and 426 million euros) and was even subjected to a budgetary freeze in 2010. This did not enhance the government's reputation with regard to creating a supportive investment eco-system.

As pointed out above, due to less context dependence, generic TIS by default have a compact and less fragmented actor structure that need to be aligned to advocate for supportive policy. In contrast, due to more context dependence, within configurational TIS much more diverse actor groups need to be coordinated. Hence, in configurational TIS the transactions cost are higher and slow down advocacy processes, which inhibit a clear guidance of the search.

F5. Market formation

Market formation progressed continuously throughout the formative phase for the onshore wind and solar PV TISs due to functioning knowledge flows, as well as a clearer guidance of search and legitimacy. For the solar industry this was also due to "a set of local initiatives (that) provided enough protected market spaces for the industry to survive" (Jacobsson and Lauber, 2006, p. 272). The guidance of search behind this continuous stream of supportive policy can be traced back to an increasingly strong advocacy coalition consisting of a variety of societal actors promoting and building legitimacy for renewable electricity technologies (Dewald and Truffer, 2011, p. 298; Jacobsson and Lauber, 2006, p. 265; Lauber and Metz, 2004, p. 617). This legitimacy in combination with a growing number of employees probably led to the implementation of the "1,000 Roofs Program", the first feed-in-tariff in 1990, the "100,000 Roofs Program" in 1999 and the "market creation with a punch" (Lauber and Jacobsson, 2016, p. 150) due to the implementation of the EEG that secured an attractive funding base for private and institutional investors (Jacobsson and Lauber, 2006).

Market formation has not yet picked up substantially in the heat TIS. The technologies required are widely available, but demand is not being stimulated by either heat production subsidies, such as the EEG, or by strict regulations.

F6. Resource mobilization

Through the 1970s, 1980s and 1990s, the onshore wind and solar PV TISs were increasingly supported by R&D spending on a national scale. Spending started in 1974 with about 20 million German marks (about 10 million euros). It fluctuated up and down (DM 300 million in 1982 and DM 164 million in 1986) (Jacobsson and Lauber, 2006, p. 261). In 2016, approximately 202 million euros were invested in R&D for solar PV and wind energies alone (excluding grids etc.). Policy makes also included market pull programs from the beginning of the 1990s. The first feed-in tariff introduced in 1990 initiated the take-off for wind power, but not yet for solar PV (Jacobsson and Lauber, 2006, p. 264). The take-off for solar power was only secured in 1998, when the new Social Democratic-Green government initiated the "100,000 Roofs Program " (Jacobsson and Lauber, 2006, p. 267; Räuber A., 2005, p. 164; Staiß, 2003, I-151). The EEG was introduced in 2000 and featured favorable conditions and billions of euros worth of investments (see institutions) that led to a steep rise in demand.

In the heat TIS, most renewable technologies were developed decades ago. For instance, the invention of the heat pump can be traced back to the mid-19th century (Obermayer- Marnach et al., 2003, p. 180). Since the development of these technologies was often not the result of a strong political necessity and societal debate, the R&D of these technologies was not as heavily funded as that of renewable electricity technologies. This spread of R&D investments continues up to the present. As mentioned above, in 2016, approximately 202 million euros were invested in R&D of solar PV and wind. The total amount invested in renewable heating technologies is only about a third of this sum (geothermal ~ 20 million euros; bioenergy ~ 30 million euros; residential solar thermal energy ~ 13 million euros) (BMWi, 2017).

Financial market pull policies for renewable heating technologies have been in place since the middle of the 1990s[13] (see institutions) and have made a continuous stream of resources available. However, the volume of these programs was substantially smaller than for electricity technologies.

F7. Legitimacy

"Legitimacy is a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions" (Suchman, 1995, p. 574). Legitimacy equips new technologies with the license to develop and is thus "a prerequisite for the formation of new industries (as well as) (...) new TIS" (Aldrich and Fiol, 1994; Bergek, Jacobsson, Carlsson et al., 2008, p. 417; Rao, 2004). To illustrate the different legitimacy dynamics in the electricity and heat IS, we follow Suchman's distinction between institutional and strategic legitimacy. Institutional legitimacy is a phenomenon for organizations "seen (as more or less) natural and meaningful" by society due to institutional alignment between society and organization(s) (Suchman, 1995, p. 576). In the case of strong alignment, organization(s) can genuinely reach out to specific resources made available by society (Suchman, 1995). In contrast, when (new) organizations and industries cannot - or not sufficiently - reap such support, they may (in addition) aim at strategically generated legitimacy by manipulating their environments. "In particular, groups of organisations (coalitions) may exert major pressures on the normative order by joining together to actively proselytize for a morality in which their outputs, procedures, structures, and personnel occupy positions of honour and respect" (Suchman, 1995, p. 592).

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[13] http://ee-waerme-info.i-ner.de/index.php?title=Marktanreizprogramm

Concerning institutional legitimacy, both the renewable electricity and heat IS were/are able to build on some initial normative approval of their technologies. However, the level of legitimacy varies: While the electricity IS profited from two intensifying discourses - the phase out of nuclear energy and climate change mitigation - the heat IS could only count on climate change mitigation.

Concerning strategic legitimacy, the actors in the electricity IS proved successful in building and maintaining a strong advocacy coalition (Jacobsson and Lauber, 2006, p. 265; Lauber and Metz, 2004, p. 617). While the nationwide organization focused on lobbying for new policy edicts (Jacobsson and Lauber, 2006, p. 264), "the green movement articulated demand for decentralised technology" (Dewald and Truffer, 2011, p. 298) in public rallies and protests.

Effective coalition building in the heat IS has not yet taken place. There are two reasons for the substantially better coalition building for the onshore wind and solar PV TISs: First, the compact actor structure induced by generic technologies is easier to coordinate. Second, the low overlap between new actors and incumbent actors in the electricity IS made it comparatively easy to stylize the fossil-based incumbents as bogeymen and to utilize the number of employees in new firms as a strategic device to legitimize action - especially since the incumbents lacked substantial investments in renewable technologies (Geels et al., 2016). The strong actor coalition made it possible to gain increasing policy support which finally resulted in the enactment of the EEG (Jacobsson and Lauber, 2006, p. 263).

There are also two reasons why no strong advocacy coalition to forge strategic legitimacy has been created in the heat TIS: First, the configurationally induced multitude of dispersed actors in the heat TIS continues to inhibit the efficient uptake of collective action. Second, due to the strongly interwoven structure of new and incumbent actors, which is mainly due to portfolio extensions by incumbent companies, the new actors affiliated with more renewable technologies seem to struggle when it comes to joining forces and delegitimizing fossil-based technologies.

A representative of a heat tech association stated:

> *"The members of the renewable heat working group seem to be more like competitors (than allies). And instead of us saying (...) 'we are all 100% renewable, we should actually hold together against the others', we beat each other up out there in the field".*
> (Interviewee #30)

As a consequence, the electricity IS was able to attract very high levels of support from local to national levels (Dewald and Truffer, 2012, p. 409; Geels et al., 2016, p. 910; Jahn, 1992), while the actors in the heat IS are still struggling to do so.

Concerning generic and configurational TIS, we learn from this analysis that the electricity IS had an advantage from the beginning with regard to institutional legitimacy. This advantage was relatively easy to extend, and this was partly due to the actor structure induced by the generic technology structure.

Table 4 and Table 5 summarize the findings of the comparison in a condensed and abstract way.

Table 4: Comparison of structural dimensions between the generic innovation systems and configurational innovation systems.

	Generic innovation systems	Configurational innovation systems
Actors	Homogeneous and compact. Many component manufacturers are tied to original equipment manufacturers. The downstream sales structures are lean.	More heterogeneous, fragmented and dispersed than in generic innovation systems.
Interaction	Networks are easily formed due to the homogeneous and compact actor structure.	The heterogeneous actor structure hinders interaction which leads to a lack of powerful networks that channel interaction.
Institutions	Due to faster network-building, it is likely that hard institutions beneficial to innovation system development are quickly established. Soft institutions are not per se directly influenced by the type of innovation system. In some cases, they may be beneficial or inhibiting.	Due to more demanding network- building, it is likely that hard institutions beneficial to innovation system development take more time and effort to develop. Soft institutions are not per se directly influenced by the type of innovation system. In some cases, they may be beneficial or inhibiting.
Infrastructure	(Incumbent) infrastructure may create certain path dependencies but is unlikely to influence the innovation system by default one way or another. [14]	Configurational TIS are by default influenced by a greater variety of (incumbent) infrastructures since these are part of the local context.

The better the fit, the easier and faster diffusion will take place. However, typically configurational technologies need to deal with large differences in local infrastructure or need to build a variety of new infrastructures, depending on the context. It is the variety in infrastructures that is a hampering factor for configurational technologies

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[14] We do acknowledge that in the case of renewable electricity the incumbent infrastructure influenced the diffusion of generic electricity technologies. For instance, the already existing electricity grid favored the option for a rather centralized system. However, we suggest that technologies or products that are even more generic in their nature would not be influenced by preexisting infrastructures.

Table 5: Comparison of the system functions' fulfilment between the generic and configurational technological innovation systems.

	Generic innovation systems	Configurational innovation systems
F1. Entrepreneurial activities	Rapid emergence of dominant designs requires relatively short periods of commercial and/or practice-oriented experimentation. Entrepreneurs can focus their abilities and resources on the development of a limited number of technologies much earlier.	Dominant designs are difficult to achieve. Only limited product and process crystallization is possible. Thus, there is a high need for continuous experimentation.
F2. Knowledge development	Due to generic technology design, knowledge development and learning takes place mostly in OEM organizations. Only limited learning takes place at the point of deployment.	Product diversity is higher in order to cater to differing local needs. A large share of knowledge development and learning takes place not only upstream but also at the point of deployment. Analytical component knowledge is codified but integrational knowledge is of a rather tacit nature, since project developers and installers are dispersed and are therefore often hindered in sharing their knowledge.
F3. Knowledge diffusion	Knowledge diffusion takes place through a limited number of rather homogeneous and quite well demarcated group of actors. This structure makes bringing actors together, establishing ties, forming networks and institutionalizing knowledge flows straightforward.	Knowledge diffusion takes place through a broader and fuzzier group of actors, which makes it harder to facilitate. Maximum knowledge is required for installers and project developers. Hence, there is a stronger need for local intermediaries.
F4. Guidance of search	Due to the rapid emergence of dominant designs, a limited variety of technologies can be suggested to policy-makers by advocacy groups to be supported in regulative and financial terms. Advocacy groups can convey a clear message, which is likely to induce policy-maker activities.	Since the variety of technologies and actors is greater, policy- makers face a higher complexity. It is harder for actors to construct coherent policy expectations and suggestions. Therefore, reaching a clear guidance of search is more challenging.

	Generic innovation systems	Configurational innovation systems
F5. Market formation	A clear technological identity fosters market formation.	Since guidance of search, legitimacy and functioning knowledge flows are harder to achieve, market formation is harder to reach.
F6. Resource mobilization	A clear technological identity fosters resource mobilization.	If guidance of search is not clear and market formation not in place due to the dispersed technological solutions, resource mobilization is likely to be hampered.
F7. Legitimation / Support from coalitions	Advocacy groups are easily formed; this fosters the process of legitimation.	The advocacy groups that can fuel legitimation are harder to form due to the greater number and variety of actors who are more decentralized and less aligned with regard to their expectations and interests.

Virtuous and vicious cycles

For the renewable onshore wind and solar PV TISs, we observe that most of the functions are well fulfilled and have created positive feedback loops that lead to a lasting virtuous cycle. The relatively quick convergence towards a dominant design has helped actors to develop (F2) and share knowledge (F3) in an efficient way. Furthermore, it was easier for actors to form advocacy coalitions that speak with one voice (F7) and lobby for solar and wind programs such as the 100,000 Roofs Program and the EEG that paved the way for the diffusion phase of these technologies and eventually created a powerful and large market. (F5).

Due to the stronger local context dependence of heating infrastructure, the heat TIS features a much larger array of technologies as well as a much higher number of local and thus geographically dispersed actors. This leads to a vicious cycle which manifests itself in less pronounced system functions such as impaired knowledge development (F2) and diffusion (F3), as well as difficulties creating legitimacy (F7). The underlying cause is a rather low level of networking and interaction. This in turn leads to poor market formation (F5) since guidance of search (F4) is not clear and does not funnel enough resources into the heat TIS for increased deployment investments or the creation and support of intermediaries. In addition, the wide array of technological solutions and the lack of dominant technology designs make it difficult for lobby groups to coordinate, act in concert and speak with one voice (F7). This, in turn, diminishes the ability and capacity to increase supportive subsidies for low-carbon heating technologies (F5) and to abate the support that fossil fuel solutions still enjoy. Furthermore, low legitimacy levels in the political arena cause a backlash against guidance of search (F4) and market formation (F5).

Our analysis demonstrated that the degree of dependence on local context has an impact on the development of the respective TIS. We showed 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. Configurational technologies such as heat technologies rely on an innovation system suffering from many problems that are directly related to the technology characteristics. We can label these configurational TIS. The severe structural and functional problems in configurational TIS result in a slow build-up and poor functioning. This impacts the time needed for a configurational technology to develop and diffuse. These, findings are very likely to be found as well in other than the here analyzed innovation systems. Therefore, no matter which innovation system is in scope, in discussions about the speed of technological transitions, it is important to take the generic or configurational character of the emerging innovation system into account.

2.5 Accelerating the development of configurational TIS

The analysis and results section showed that the generic onshore wind and solar PV TISs and the configurational heat TIS differ fundamentally regarding structural dimensions and system functions. The attributes of the configurational heat TIS lead to a slower pace of transition in the heat sector in comparison to the electricity technologies in scope. By introducing the notions of configurational and generic TIS, this paper contributes to the literature on innovation systems and to the literature on the temporality of transitions. Due to the higher local context dependence, configurational TIS are likely to develop a greater variety of technological solutions and a more fragmented actor structure. The system that develops in the process is more complex and therefore more demanding to govern. This results in less cumulative causation and therefore slower development in comparison to more generic TIS. We showed that the dynamics of technological innovation systems are likely to be affected by the level of context dependence. We also showed that TIS that are more dependent on local context and thus of a configurational nature are likely to be more fragmented and dispersed with regard to technologies and actor structure. A more fragmented actor structure makes it harder to interact efficiently, form networks and lobby to change institutional settings. Our analysis further indicated that the distinction between configurational and generic TIS can be understood as a predictive measure for functional developments and eventually the pace of TIS development and consequently the speed of transition. The TIS studied should only be seen as examples of configurational and generic TIS.

It is important to note that the concept of generic TIS and configurational TIS is a relative one (Figure 6). The analyzed renewable electricity TIS also entails configurational elements, for example, the deployment of solar PV panels may also be influenced by the layout of the roof. On the other hand, the renewable heat TIS also entails generic elements, for example, as once an operational configuration has been implemented, single components can be easily substituted. Overall, the distinction between configurational and generic is a matter of degree (Fleck, 1993, p. 34), but is nevertheless helpful for analysts.

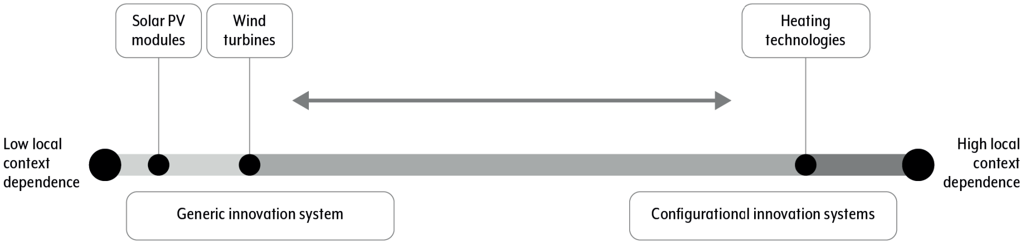

Figure 6: Technological innovation systems on a context dependence scale.

The degree to which a specific TIS is configurational or generic is not fixed but spatially situated and temporal in nature. Technological innovation systems may be characterized as currently configurational in one place but may become more configurational or generic in other places, due to other institutional preconditions. For instance, in the Netherlands large numbers of residential buildings are often built in one go and are remarkably similar (Kieft et al., 2016, p. 38), whereas in Germany houses are built one by one and much less similar. Therefore, the heat TIS in the Netherlands may be more generic than in Germany. Furthermore, over time a TIS may develop more generic features and vice versa.

Furthermore, prioritizing large wind turbines with a horizontal-axis three-bladed design steered the renewable onshore wind TIS more strongly in the direction of a generic TIS than smaller, decentralized systems would have done. Thus, crystallizations towards more generic designs and the connected efficiency gains may be promising avenues for the development of generic TIS in order to decrease the overall system complexity. For the renewable heat TIS, this could mean fostering solutions that can be industrialized such as prefabricated houses with a limited number of predesigned renewable heating systems based on the heating source used.

Despite these suggestions for rather technology-centered means to reduce system complexity, analysts and policy-makers should be aware that identifying and addressing the sources of both technical and non-technical complexity (and their interplay) is fundamental when discussing the process of sustainability transition. Ignoring this may lead to the acceptance of solutions that are less beneficial from a societal viewpoint.

We acknowledge that the configurational structure of the renewable heat TIS is not the only factor that influences the pace of technological innovation system development. External trends and events (Geels 2002; Bergek et al 2015), as well as other internal processes also have an impact on the pace of development in TIS. For instance, the nuclear disasters in the 1970s and 1980s are likely to have helped mobilize societal actor groups in Germany to push for a transition in the electricity sector (Jahn, 1992). Recognizing this, we argue that the degree of local context dependence is not the only factor accelerating or decelerating fundamental shifts, but we conclude that it is indeed one of the factors influencing the speed of transitions.

The practical implication of this study is that system builders active in configurational TIS have options to speed up the development and diffusion of configurational technologies. First and foremost, the groups and individuals in the TIS need to get organized. A collective identity and strategy need to be developed to overcome the dispersed character of configurational TIS. Second, more efforts on standardization of technologies, technological systems and practices is necessary to drive down cost and hereby accelerate the speed of learning and overall TIS development. Research is needed on how these two practical implications can be implemented and how and what barriers actors face on their way to speed up the development pace of configurational TIS.

3

On accelerating the development of configurational innovation systems – the case of district heating in Germany

Wesche, J. P., Negro, S. O., Dütschke, E. and Hekkert, M. P. 'On accelerating the development of configurational innovation systems – the case of district heating in Germany', under review in *Energy Sources, Part B: Economics, Planning, and Policy.*

3.1 Introduction

Technological innovations play an important role in strategies to achieve climate goals and to move forward in the transition of energy systems towards sustainability. They are developed and diffused by networks of actors that are embedded in a specific institutional context. This embeddedness of technological innovations is captured by the technological innovation system (TIS) framework (Hekkert, Suurs et al., 2007). The framework has been applied in many studies to understand the typical dynamics of emerging technological fields (Hekkert, Harmsen, Jong, 2007; Kieft et al., 2016; Musiolik and Markard, 2011; Negro et al., 2008).

Most TIS studies analyze technological developments that are little context-dependent. These technologies can be produced in series in factories and sold across the globe; they do not need to adapt to local contingencies. Examples of such technologies are vehicles (Wesseling et al., 2014), solar panels (Dewald and Truffer, 2011) and wind turbines (Johnson and Jacobsson, 2003; Reichardt et al., 2016). We refer to these as generic technologies (Fleck, 1993). It is only recently, that the literature has started to acknowledge that TIS can have different characteristics and development patterns (Binz and Truffer, 2017). Among them is the level of local context dependency (Wesche et al., 2019).

Binz and Truffer (Binz and Truffer, 2017) argue that the production and valuation of technologies can be more or less context dependent. Wesche et al. (2019) coined the term configurational innovation systems for innovation systems that foster the development and diffusion of technologies that are strongly dependent on the local context and need to be configured with regard to specific local contingencies.

The purpose of this paper is to contribute to a better understanding of the dynamics of configurational innovation systems and the repercussions for policy. Accordingly, we present the findings from an empirical a study of the German non-urban district heating TIS. This TIS is of configurational character, since the implementation of district heating technologies are strongly dependent on the local implementation context (Wesche et al., 2019). Furthermore, analyzing and deriving policy recommendations for this TIS makes sense from an empirical viewpoint, as the German government perceives the diffusion of district heating systems using low-carbon sources as a key technology to reduce greenhouse gas emissions in the built environment in

Germany (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), www.bmub.bund.de, 2016, p. 41).

3.2 Analyzing and designing policy for configurational innovation systems

The development and diffusion of (technological) innovations takes place in socio- technical systems, which are at the core of the technological innovation system framework (TIS) (Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008b). The key idea thinking about innovation systems is that innovations do not develop in a vacuum, but are embedded in socio-technical structures – made up of networks of actors, rules and infrastructures – that influence the development and diffusion of an innovation. Actors are differentiated into categories such as individuals, organizations, and networks (Wieczorek and Hekkert, 2012, p. 76). Interaction takes place between individuals, networks and organizations (Wieczorek and Hekkert, 2012, p. 76). Furthermore, rules are labeled as institutions, and can be divided into "hard" institutions such as legislation, standards or other codified rules, and "soft" institutions, which encompass norms, values as well as a "set of common habits, routines and shared concepts used by humans in repetitive situations" (Wieczorek and Hekkert, 2012, p. 76) (Crawford and Ostrom, 1995). 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 et al., 2012, p. 3838). Infrastructure encompasses three categories: knowledge infrastructure, physical infrastructure, and financial infrastructure (Wieczorek and Hekkert, 2012, p. 77).

When networks of actors engage in activities that contribute to the development and diffusion of innovations, an innovation system will start to function. How well the innovation functions can be assessed by using the "functions of innovation systems" framework. Several sets of functions have been suggested (Bergek, Jacobsson, Carlsson et al., 2008; Hekkert, Suurs et al., 2007). In our study, we used the set of seven functions proposed by (Hekkert, Suurs et al., 2007) (Hekkert, Suurs et al., 2007): (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 6).

Table 6: Description of seven key system functions (Reichardt et al., 2016, p. 12) based on Hekkert, Suurs et al. (2007)

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 in.
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 behampered.
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 take adoption decisions

Innovation systems are complex. When actors engage in certain activities, it can have positive or negative impacts on other elements of the innovation system and in turn impact the activities in which they will subsequently engage. Virtuous and vicious cycles emerge, which are important for understanding innovation system dynamics (Hekkert, Suurs et al., 2007, p. 426).

When analysts assess that an innovation system is not functioning well, they should be interested in the causes that explain poor functioning. Often, such causes are found in the structure of the innovation system, and are labeled systemic problems. Systemic problems are problematic elements in the system structure that inhibit an innovation system from functioning well (Negro et al., 2012; Wieczorek and Hekkert, 2012). The consequences for policy are that when the functional performance of a TIS is unsatisfactory, policymakers should strive to design policies that impact structural elements in such a way that system functioning is improved.

After the development of the TIS framework, many authors started to apply the framework in empirical studies (Dewald and Truffer, 2012; Markard and Truffer, 2008a; Negro et al., 2007). Recently, building on the rich empirical work that has since accumulated, authors have started to acknowledge 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, Schmidt et al., 2016), the geographical scalarity (Binz and Truffer, 2017), the mode of innovation and knowledge generation (Binz and Truffer, 2017), and as the level of local context dependence (Wesche et al., 2019). In this paper we focus on local context dependence.

Technologies that are little context-dependent can be produced in series; they do not need to adapt to local contingencies and can be easily substituted by more efficient and up-to-date technology. Such technologies can be referred to as generic technologies (Fleck, 1993) and the respective TIS as a generic innovation systems. 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, technologies that are strongly dependent on the local context always need to be specifically configured with regard to local contingencies and therefore they be referred to as configurational technologies (Fleck, 1993). Such technologies include domestic heating related technologies forming a configurational innovation system (Wesche et al., 2019).

We suggest that the differentiation between the two types of innovation systems (generic and configurational) leads to two general repercussions for TIS-based research (see Table 7). First, we suggest that these two types of innovation systems call for different research approaches. Most importantly, we argue that due to the stronger dependency on the local context, both the local level and the capture of its heterogeneity are substantially more relevant when studying configurational innovation systems. By contrast, to analyze a generic TIS, a focus on the national or other overarching level is likely to be sufficient to identify systemic problems and derive policy recommendations. However, since technology implementation in configurational TIS takes place in a variety of local contexts, it is necessary to take these specific local conditions of experiments into account and address them when analyzing configurational innovation systems. Therefore, we suggest, that data collection should also be conducted in relation to local implementation in order to grasp and develop a sound understanding of the local context specificities and their variations. Otherwise, conclusions and policy recommendations are likely to miss relevant issues and, thus, will not be able to influence the innovation system in the expected direction.

Second, we argue, that policymaking in configurational innovation systems needs to resonate with the stronger local context dependence. National or European policies are always generic by definition. However, their design can be more or less able to address local contingencies. For example, non-specific policies such as feed-in-tariffs were able in the 2000er years 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. Due to such problems, the efforts required for a configurational innovation to diffuse are substantially larger than for generic innovations. Therefore, it not sufficient to implement merely incentive-based, technology-specific policy instruments. Rather, policies need to be more encompassing and entail a comprehensive set of specific policy instruments. For example, they need to create smart innovation system structures that enable local actors to cope with the high level of context specificity.

In the following sections of this paper, we apply the above-discussed theoretical propositions to the case of the German non-urban district heating TIS in order to learn whether they apply. In the methods section we outline a possible approach to how to collect adequate data on configurational TIS. In the analysis section we show that in configurational TIS not only are crucial decisions are taken at the national level, but also that policymaking needs to consider the local context dependence of configurational innovation systems. Accordingly, the local-context dependence is taken into account when formulating policy recommendations for accelerating the non-urban district heating TIS.

Table 7: Differences for generic TIS and configurational TIS concerning data collection and policy making

	Generic TIS	**Configurational TIS**
Data collection	In generic TIS data can be collected by interviewing national experts only.	Data collection needs to take account of the local contingencies of configurational innovation systems. Data need to be collected not only at the national level, but also at the local level.
Policy making	Generic TIS can be stimulated focusing on national incentivizing policy.	To stimulate the performance of configurational innovation systems, policies need to be more diverse and they may include not only incentives but also broader policy instruments. Furthermore, policy needs to emphasize the diffusion of knowledge.

3.3 District heating as a configurational innovation system

In this section we give a brief overview over 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 has pledged to decrease substantially the carbon emissions from its building stock in order to reach its goals for reduction in greenhouse gas emissions (Bundesministerium für Wirtschaft und Energie, 2010, p. 22). One strategy instrument to attain this goal is the broad diffusion of district heating systems using low- carbon sources such as renewable sources and waste heat sources (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB), www.bmub.bund.de, 2016, p. 41). In 2016, less than 15% of German households was supplied by district heating systems (Bundesverband der Energie- und Wasserwirtschaft, 2017, p. 8). This is little, compared with, for example to Demark and Austria where the share was respectively ca. 63% in 2015 (Danish Energy Agency, 2015, p. 4) and 26% in 2017 (Fachverband Gas Wärme, 2018, p. 21). The general advantage of district heating is that heat production takes place more efficiently compared with individual building heating solutions. These efficiency gains are generated by higher economies of scale (Lund et al., 2014, p. 1), which can lead to fewer greenhouse gas emissions. Furthermore, more CO_2 emissions can be avoided if the heat sources are carbon neutral.

New district heating projects have two general application cases. Either they are implemented in areas with pre-existing buildings, or they are implemented in newly developed neighborhoods. As of 2017 in Germany 1454 district heating networks were installed (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., p. 18). 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). This is insufficient, considering the potential of district heating altogether and the challenges that are posed by the decarbonization of the German residential heating sector.

The non-urban district heating TIS is configurational in character, as heating grids cannot be produced in series, and they are largely contingent upon the local context. Hence, each new project needs to be specifically designed to fit with the local contingencies. These 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, and the local topography. Since district heating projects are complex configurational projects, the implementation of each project will be unique and the project will differ from all other projects.

3.4 Methods

In the theory section we have argued that while, for generic TIS, it may suffice to conduct interviews with actors at the national level only, this may not be adequate when analyzing configurational TIS. By contrast, since technology implementation in configurational TIS takes place in a variety of local contexts, it is necessary to include specifically these local contingencies in the data collection. For this reason, we chose a two-tiered approach in our study.

Frist, we conducted 20 interviews with actors that initiated or substantially supported the successful implementation of low-carbon district heating systems, namely, project developers, company and industry representatives, local and regional politicians, and representatives of utilities and communities (see Appendix A). We chose successfully to focus on 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. To create a representative sample, we chose four district heating systems with contrasting characteristics. The projects differed according to the settlement structure, temperature levels in the grid, type of heat source, and the institutional background of the grid operator (see Table 8 for an overview).

Second, we conducted nine interviews with experts from the national level, who were asked questions about the non-urban, district heating innovation system as a whole. These nine interviewees were national-level experts in the German heating sector (see Appendix A). They were selected due to their knowledge of the scope of TIS and being 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 the focused on the national level and the interviewees' experiences in other district heating system related projects. The project-related interviewees were first asked about the project implementation procedure. Thereafter, they were asked about the factors that influence the emergence of non-urban district heating systems with a special focus on challenges, and finally they were asked for recommendations on 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 6. The interviews were

Table 8: Overview of four non-urban district heating systems and interviews conducted

	Supplied buildings	Grid length	Heat generation technology	Operator	Type of buildings	Interviews conducted
Project A	Ca. 270	15,5	Waste heat, wood chips	Regional operator	Existing neighborhood	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 from 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 9: Overview of the nine expert interviewees

ID	Position	ID	Position	ID	Position
#21	Energy researcher	#24	Representative of a heat technology think tank	#27	Manager in a 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 sweeper association	#29	Manager in a pipe tech company

coded independently by the first author and a research assistant at Fraunhofer ISI. Differences in the coding results were analyzed and in cases where classifications differed, ambiguous categories were refined and non-fitting codes were deleted.

3.5 Innovation system analysis

This section is divided in three main subsections. The first subsection describes the structure of the non-urban, low-carbon district heating innovation system (hereafter referred to as the district heating innovation system). The second subsection we describe the key processes and challenges throughout the development stages of the four analyzed non-urban district heating projects. Lastly, we with offering insights into the performance of the district heating innovation system's functions.

Structural elements of the German district heating TIS

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

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 they 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 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, and 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.

Interaction (networks)

Interaction is important at both the national 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 in the German heating sector coalition building is not yet well established[15]. This applies to the domestic heat sector as a whole, but is also likely to be the case for the district heating innovation system. 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 innovation systems: local dynamics and conditions are heterogeneous and may require different interaction and communication approaches.

Institutions

As indicated in the theory section, 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 & BMU, 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.

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[15] Wesche et al. Actor coordination and division in sustainability transitions – evidence from the German domestic heat system, under review in *Environmental Innovation and Societal Transitions.*

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 pre-existing neighborhoods, soft institutions play out with more force. Residents living in such neighborhoods seldom desire to change their heating infrastructure while the current heating systems continue to operate, and the installation of new heating infrastructure involves extra effort, noise exposure, and sometimes high financial investments.

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 tap into. 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.

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 a heuristic 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 fully 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 7).

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, 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 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 looming.

The above-mentioned examples show that the initiation processes of the analyzed non-urban district heating systems were all acts of serendipity. 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 t*hat stimulates or obliges project initiation.*[16] 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:[17]

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

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

[17] 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.

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, Interviewee #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 colleagues in project B and C he actively supported the project and convinced other members of the local council to back and endorse the district heating project (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, whereas 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 are inclined to restrict the action of their municipality to a minimum:

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

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 suppor*t, which suggests that one reason for the limited number of new projects is likely to be lack of local support altogether. Both systemic problems hamper the experimentation function.

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 conduct to acquire the relevant knowledge and information to prepare for project planning and implementation.

Successful implementation of non-urban district heating projects requires ample knowledge - often technical and regulatory. Technological knowledge includes knowledge about the functionality of specific technologies, configurability of and interplay between technologies as well as market availability of technologies and components. Regulatory knowledge includes knowledge 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 report that the collection of knowledge is sometimes an intricate process because technological and regulatory knowledge is dispersed, fragmented and not easy to locate. This leads to substantial efforts that are required in order to gather all essential pieces of information. Sometimes, project initiators struggle to gather the right information for their respective 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; other buildings were more or less estimated. However, we (as project developers) can't base a project (planning process) on this kind of data".*
> (Interviewee #3).

This points to another systemic problem, namely the lack of easy accessible and well- structured knowledge, which hampers the experimentation function.

Initiator teams can choose between two approaches to collect knowledge. They can either draw on intermediary organizations or the try to conduct the knowledge accumulation process themselves. Since lay initiators might be overwhelmed with the required knowledge, the second strategy is likely to increase the probability of project success, (ID #4, ID #8, ID #3, ID #11).

The project development in project A shows the integral role that a knowledge intermediary - in this case a general contractor - can play for the success of non-urban district heating systems. An initiator group had established itself in the beginning of the 2000ies (ID #2, ID #3, ID #4). They had successfully lobbied the mayor to be able to conduct a feasibility study. Furthermore, they had conducted a number of public meetings as well as house door visits and collected substantial data on the heat supply needs and the willingness of households to connect to a potential district heating system. However, due to insufficient knowledge and resources the project went into hibernation until the beginning of 2014 when a general contractor was invited by a local business man and other residents to restart the project (ID #1, ID #4). This general contractor took advantage on knowledge that the company had collected 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 a year. Also project B and C searched for help by intermediary organizations. For instance the initiators in project B managed to establish cooperative ties with a regional technological university of applied sciences (ID #12, ID #13), while the initiators in project C took advantage of a regional business development agency that had some limited experience with district heating (ID #15, ID #16, ID #17).

If project initiators choose to not rely on intermediary organizations, but to accumulate the knowledge by themselves they are likely be faced with substantially more required effort. Only the initiators in project D were capable of pursuing this second approach. At this 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).

Currently, finding appropriate intermediaries is not easy (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 easy accessible and well-structured knowledge, t*his lack of sufficient knowledge intermediaries hampers not only the directly relatable knowledge exchange function, but indirectly also the experimentation function as well as the knowledge generation function, since these demand ample knowledge exchange to take place.

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, also in the planning stage project initiators need to decide 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 in order 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 large city district heating systems. 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 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".*
> (Interviewee #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).

Similarly, as in 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.

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 currently installed heating infrastructure will still be operating well and local residents will not have an urgent need to change their heating technology. Furthermore, changing heating infrastructure involve nuisance and requires extra effort.

In existing neighborhoods in Germany, residents often rely on an existing heat supply that works well, with a low level of effort required. At any given time, usually only a limited share of households in an area needs to replace their heating infrastructure. Hence, a genuine demand for new heat technology in pre-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 in 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".*
> (Interviewee #17)

Our empirical data showed that in the current state of innovation system development, potential customers are often not interested in district heating systems. For instance, some residents have a strong preference for being self-sufficient (ID #21). Others tend to favor investments in kitchens or bathrooms over investments in heating infrastructure (ID #21), which also by default decreases 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 to overcome a lack of interest in the projects in scope, such as town hall meetings or door-to-door visits, the data show that regardless of the local context, project initiators in the studied cases used financially attractive contracts as their preferred measure 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.

Functions performance

The findings from our analysis suggest that most functions are not performing smoothly. Figure 7 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 7 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. In the case of the analyzed non-urban district heating TIS rather than the nascent non-urban district heating TIS, negative feedback loops keep functions from accelerating their performance. Even though there are some promising system structures, such as government goals and financial incentives, some functions continue to perform poorly and therefore also hamper the acceleration of other functions' development.

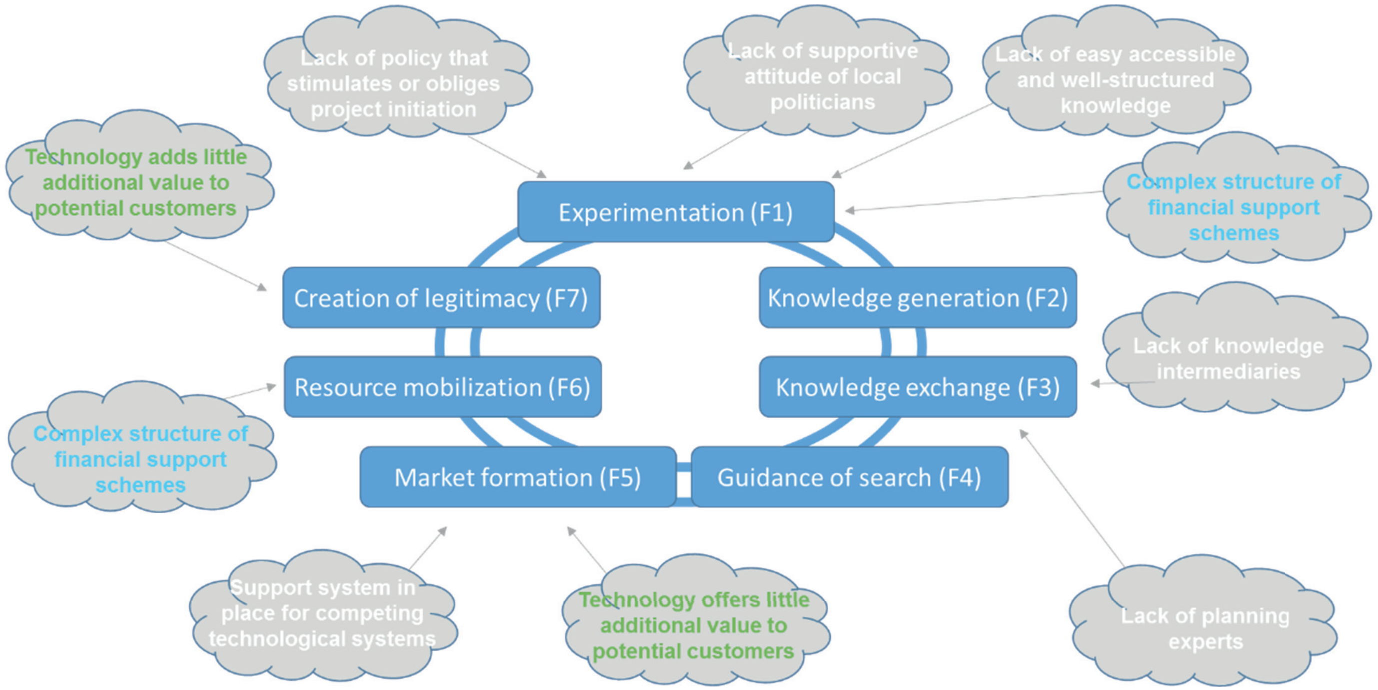

Figure 7: Systemic problems that hamper the functional performance of the German non-urban district heating TIS

3.6 Implications for studying and policy making in configurational TIS

The findings from our analysis of the innovation system underline the categorization of the German non-urban district heating TIS as a configurational TIS. The implementation of each new project is strongly influenced by local contingencies. For example, the factors that triggered the initiation of each of the four case projects, as well as the choice of the heating source, depended on the local context and existing actor constellations. This finding supports our proposition that a meaningful analysis of a configurational TIS needs to take account of the local level.

With regard to policymaking, we found that in configurational innovation systems systemic problems are likely to be prevalent on the local scale and therefore policymaking should take this stronger local context dependence into account. Hence, for the diffusion of configurational innovations, policies need to lead the creation of smart innovation system structures that enable local actors to cope with the high level of context specificity. One way of organizing this is the creation of dedicated knowledge intermediaries that help to support non-urban district heating and that are capable of dealing with the large variety of needs in different projects. This implies a high level of knowledge about district heating technology, project organization, and necessary institutional change. It also implies easy access and on-demand advice for all actors that are considering district heating. Increasing the number of knowledge intermediaries, such as local or regional energy agencies that are equipped with heat-related knowledge, will stimulate knowledge exchange and support project initiators, local political decision- makers, and potential customers of district heating systems. Such intermediaries would also be key actors in facilitating vertical and horizontal knowledge exchange, and thereby they would empower local actors to implement new district heating systems. Furthermore, it seems advisable to create centralized knowledge bases that are easy for project initiators to find and navigate. Apart from that, ministries or other governmental bodies should facilitate forums where local actors could bring their concerns to the attention of policymakers at the national level.

Our empirical analysis of the systemic problems showed that such a way for policymaking is not yet in place in the German district heating innovation system. This is not strange, as most of Germany’s success in renewable energy is related to policies that facilitated the diffusion of generic technologies.

In addition to the establishment of dedicated organizations to boost innovation system performance, some more generic measure are likely to have high impact. Such organizations relate to regulation, finances, and knowledge.

First, the findings from our analysis showed that all projects suffer from a lack of policies that stimulate project initiation and a lack of a supportive attitude by local politicians. Both hamper the project initiation process. To overcome this problem, municipal heat planning should become a compulsory component of municipal services and targets for reductions in carbon emissions should be implemented at municipality level.

Second, the findings from our analysis showed that the case projects suffered from remaining financial support for fossil-fuel based heating technologies and from complex financial support structures. Therefore, a logical policy improvement would be the reduction of support for heat technologies that run on fossil fuels. Furthermore, policymakers should revise current support schemes aiming to reduce complexity for those applying for financial support.

3.7 Conclusions, limitations and further research

The theoretical aim of this paper is to contribute to a better understanding of how to study and formulate adequate policies to accelerate the development of configurational TIS. The empirical aim of the study on which this paper is based was 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. Thus, analyst will able to provide for 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. Specifically, the sole focus of national-level policies that do not take the local context into account seems insufficient to overcome the multitude of local context-related obstacles. 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 increase the pace of the innovation system's development. 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 limitations of our analysis mainly relate to 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 consider the data base sufficient for our aim. Second, probably the most important shortcoming is that we only studied successful cases, yet unsuccessful cases might have revealed further problematic issues. 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.

4 | Actor coordination and division in sustainability transitions – evidence from the German domestic heating system

Wesche, J. P., Negro, S. O., Brugger, H., Eichhammer W. and Hekkert, M.P. 'Actor coordination and division in sustainability transitions – evidence from the German domestic heat system' resubmitted to *Environmental Innovation and Societal Transitions* after major revisions.

4.1 Introduction

The pace of sustainability transitions (Sovacool, 2016) is a critical factor for achieving the UNs Sustainable Development Goals in 2050. The pace of transitions is often hampered by unsupportive institutional environments that impede sustainable niche configurations and prevent them from flourishing. This is not really surprising, given that institutional settings result from co-evolutionary processes that align institutions and technological systems (Unruh, 2000). When innovations differ radically from existing technological systems, it is logical that they will not have a good fit with the currently institutionalized rules of the game. A key strategy for actors interested in the diffusion of novel socio- technical configurations is to engage in institutional work (Lawrence et al., 2011) in order to initiate institutional change.

In the literature on institutional change (Rao et al., 2000; van de Ven, 1993; Wijen and Ansari, 2016) and on socio-technical transitions (Geels et al., 2016, p. 904; Hekkert, Suurs et al., 2007, p. 425; Raven et al., 2015, p. 178; Smith and Raven, 2012, p. 1026) it is widely acknowledged that institutional change relating to innovations and transitions seldom originates from individuals. It is best regarded as a collective activity. The collective activity is often the result of a set of uncoordinated activities, as proposed by the framework of institutional work (Lawrence et al., 2011, p. 55), but actors also have the option to orchestrate strategically a process of collective action. van de Ven (1999) describe this approach as “running in packs.” Entrepreneurs who share an interest in the development and diffusion of novel technology collectively engage in institutional work to create more favorable institutional conditions. Hargrave and van de Ven (2006) have developed a collective action model of institutional innovation by merging insights from innovation management and the social movement literature. The generative mechanism that leads to collective action is the shared recognition of an institutional problem among groups of social or technological entrepreneurs (Hargrave and van de Ven, 2006, p. 876). In this paper, we explore this shared recognition and apply it to sustainability transitions.

To date, the sustainability transitions literature has focused on collective action to create institutional change by groups of entrepreneurs who share an interest in the same technological developments (Musiolik and Markard, 2011; Planko et al., 2016). However, in the case of sustainability transitions, often several alternative technologies are developed that all hold some promise to overturn the dominant socio-technical regime (Geels, 2004). In an ideal case, we may also expect advocates of different novel technologies – often labeled niche actors – to "run in packs" because they are all likely to experience a poor fit with existing institutional structures. Coordinated action to create critical mass and therefore accumulate institutional influence is a logical strategy because new players often lack the institutional power to be effective in institutional change processes in the early stages of development. However, depending on the specificities of the technologies in question, actors operating in different niches may have different perspectives on the changes required in institutional structures. The different perspectives may hamper collective action.

In this paper, we focus on how actors from different niches interact with each other, and how this is influenced by the specificities of the respective technologies involved. Following Sandén and Hillman (2011), we assume that some technologies fit well together in transition processes and others do not. There may be several different reasons for the fit, such as complementarity in the service provided by the actors, or a shared technological infrastructure. In cases of a good fit, we can expect those supporting the different technologies to share an interest in specific institutional reforms that benefit all of them. We measure the fit between the interests of different niche actors by focusing on their visions of the desired end states of socio-technical transitions. If their visions overlap strongly, we expect a higher degree of shared interest and therefore a higher likelihood of cooperation in institutional change activities than in the case of highly diverging visions.

The existing literature does not focus on what determines the cooperation of actors from different niches and the subsequent emergence of strong coalitions in socio-technical transition processes. This paper aims to enrich the understanding of this topic. Understanding the determinants of coalition formation may also shed light on the reasons for differences in the pace of transformation processes. The research question that we aim to answer is: How do the similarities of visions regarding desired end states of sustainability transitions determine the cooperation between actors supporting different emerging socio-technical configurations?

As an empirical case, we focus on the German residential heating sector, which can be characterized by the large variety of technologies with decarbonization potential and by its slow pace of transformation towards decarbonization (Wesche et al., 2019). One major reason for this slowness is the lack of a policy schemes that foster low-carbon heating technologies by aligning policy instruments with the requirements of these technologies. For example, while there is some financial support for low-carbon technologies, technologies powered by fossil fuel continue to enjoy substantial financial support (co2online & BMU, 2019). This problematic institutional alignment may be due to a scattered lobbying landscape and a lack of cooperation between niche actors. We specifically focus on industry associations and their connections with other industry associations as a proxy for cooperation between niche actors. We focus on those industry associations that represent a specific technological field, such as heat pumps, heat grids and insulation technology.

4.2 Coalitions in sustainability transitions

Institutional change and the role of coalitions in facilitating transitions

Sustainability transitions are understood as far-reaching changes in socio-technical systems aimed at providing specific societal functions, such as energy supply or mobility, in more sustainable ways (Markard et al., 2012). Novel socio-technical configurations that can contribute to a more sustainable provision of societal functions emerge in niches “but can also be a result of endogenous regime change” (Berggren et al., 2015). For a transition to take place, the novel configurations need to develop and grow, and eventually replace the non-sustainable regime configurations that are often supported and protected by incumbent actors. Transitions are not imposed from the outset, but can be characterized by a series of system-endogenous dealignment and realignment processes that encompass institutions, technologies, and actors. For example, preexisting institutional structures are often aligned with regime technologies and practices and they need to be amended so that more novel socio-technical configurations can thrive (Fuenfschilling and Truffer, 2014).

In this paper we focus on institutions as one element of socio-technical systems that needs to be dealigned and realigned in order to create supportive environments for novelty to thrive. To ensure a common understanding, we draw on (Crawford and Ostrom, 1995, p. 582) who define institutions as the “enduring regularities of human action in situations structured by rules, norms, and shared strategies, as well as by the physical world.” One way to differentiate between specific institutions is to divide them into “regulative, normative and cognitive structures, e.g. norms, standards, values, cultural expectations or regulations, which have evolved in accordance with certain technologies” (Fuenfschilling and Truffer, 2016, p. 298; Scott, 1995).

In the innovation science literature, as well as the literature on socio-technical transitions, authors acknowledge that far-reaching institutional change is not triggered by individuals, but that institutional environments can only be decisively influenced by well- organized collective action, such as coalitions of actors. In the innovation science literature “the process of institutional change is often [known as] a political process of mobilizing campaigns to legitimate a social or technical innovation” (Hargrave and van de Ven, 2006, p. 875; Rao, 2004). Actors are known to “run in packs” (van de Ven, 2005, p. 365) or to create new paths for innovations to prosper “through the distributed efforts of many” (Garud and Karnøe, 2003, p. 296). This resonates well with the literature on innovation systems, in which actor-driven “coalitions can function as a catalyst” to build legitimacy and eventually “may become powerful enough” to incite “the spirit of creative destruction” (Hekkert, Suurs et al., 2007, p. 425; see alsoMusiolik and Markard, 2011; and Planko et al., 2016).

Similarly, in the literature on socio-technical transitions, system-level change is seen as “enacted through the coordination and steering of many actors and resources” (Smith et al., 2005, p. 1492). For instance, Ulmanen et al. (2009, p. 1415) suggest that “the creation of a protected space (for a new socio-technical configuration) involve(s) dedicated lobbying by a variety of actors joined in advocacy coalitions.” However, such coalitions not only need to create a protected space by “institutionalising niche practices” but also need to become sufficiently powerful to be able to establish them as real alternatives to “routines in socio-technical regimes” (Smith and Raven, 2012, p. 1030). With regard to the composition of coalitions in transitions, Jacobsson and Bergek (2004, p. 822) suggest that coalitions “may include many types of organizations and actors, such as universities, private and non-commercial associations, media, politicians at different levels and elements of the state bureaucracy. However, individual firms and related industry associations play an especially important role in the competition over institutions.”

Overlapping visions as a proxy for cooperation

While transitions scholars often refer to coalitions as agents of change, there has been rather little coverage in the sustainability transitions literature of the reasons for coordination and engagement in collective advocacy. Embedding our line of argument in previous strands of the sustainability transitions literature, we display that expectations are key for coordinating collective advocacy and we propose that especially shared visions of the future can be used as a predictor for coordinated activity and emergence of coalitions.

Research on expectations and visions in the field of sustainability transitions are in most cases grounded on concepts arising out of the "sociology of expectation" which has been substantially dealt with in the science and technology studies (STS) (Borup et al., 2006; Brown and Michael, 2003). In the STS induced sociology of expectations, technological expectations are defined as "real-time representations of future technological situations and capabilities" (Borup et al., 2006, p. 286). These representations can be complex scenarios or imaginaries that "can include for example (a) technology at stake, its future markets, and its societal context." As such they "provide a guiding structure in emerging technological fields," which structures "the activities of innovative actors" (van Lente et al., 2013, p. 1616). When more and more actors share similar expectations, these expectations can transform into a collectively held vision or image of the future which then "become(s) (an) accepted part of the social repertoire" (Kriechbaum et al. 2018 P. 77, see also Conrad 2006), "which cannot be ignored even by those that do not share its ideas" (van Rijnsoever et al., 2014, p. 639). When this happens these visions of the future can become performative and "turn from more or less specified rhetorical figures in to more obdurate forces that shape the evolution of an emerging technological field" (van Lente et al., 2013, p. 1616).

These conceptualizations have been taken up and echoed in sustainability transitions research where visions have been acknowledged as an important element for the destabilization of outdated socio-technical regimes and emergence and consolidation of novel socio-technical configurations (Geels and Schot, 2007b, 2007a; Hansen and Bjørkhaug, 2017; Jørgensen, 2012; Loorbach, 2010; Späth and Rohracher, 2010). For example Berkhout (2006, p. 304) suggests, that in "processes of regime transformation, future visions about the functions, order and means represented by the regime are extremely important." This is because regimes with insufficient "adaptive capacity to respond" to selection pressures that challenge the current regime and that are connected to strong and morally compelling visions will not sustain (Berkhout, 2006, p. 304).

The key function that visions fulfil is that they help envisioning desirable futures and thus motivate socio-technical change, even though "end-points (of transitions) are highly contested or only partially understood" (Smith et al., 2005, p. 1506).

For visions to be powerful, and to stimulate change they need to be aligned to coordinate activities of groups that support them (Geels and Schot, 2007a, p. 402). Such alignment of visions can be facilitated by "intermediaries (that) act as brokers between multiple priorities, interests and knowledge pools" (Kivimaa et al., 2019, p. 1067). The guiding nature of visions in transition processes are also picked up in transitions management and in the technological innovation systems literature. In the transition management perspective, "the term 'guiding vision' depicts an instrument in an agenda building process with regard to long-term policy goals and transformation strategies" (Späth and Rohracher, 2010, p. 451). Visions "function as a framework for formulating short-term objectives and evaluating existing policy" (Rotmans et al., 2001, p. 23). To be successful and drive socio-technical change Rotmans et al. (2001, p. 23) suggest that "visions must be appealing and imaginative and be supported by a broad range of actors." In the technological innovation system literature visions are a key component of the guidance of the search function which - when fulfilled - helps channeling scarce resources towards socio-technical solutions that help bringing about an envisioned future (Bergek, Jacobsson, Carlsson et al., 2008; Hekkert, Suurs et al., 2007).

Concerning the characteristics that make visions influential, Smith et al. suggest that a vision should ideally be backed and endorsed by influential and credible supporters, it should contain a certain degree of 'interpretative flexibility', and at best it should feature a general fit with the "cultural and political context, in which it is propounded" (Smith et al., 2005, p. 1507).

Based on this overview of the role of visions in transitions studies, we hypothesize that actors with similar visions of the future are more likely to coordinate their actions than actors with dissimilar visions. The key reasons for this is that due to similar visions they are also likely to have a similar understanding of what changes are needed to be pursued. While the functions of visions have been developed and discussed (Smith et al., 2005), dimensions that visions sustain of and how these can be measured have to the best of our knowledge not been developed so far. Yet, we doubt that clear sets of dimensions that constitute visions exist and can therefore be generally recognizable. We rather argue, that due to the plethora of visions for system development, relevant dimensions will need to be explored and specified in the context of the system in scope. For this reason, in the analysis section we will follow a rather grounded approach to determining relevant vision dimensions.

Characteristics of coalitions in sustainability transitions.

Sustainability transitions are complex and encompass a large variety of actors, some of whom are interested in reinforcing current practices (regime actors) and others who want to challenge them and propose novelty and change (often niche actors). So far, institutional work and related concepts have generally been analyzed in single technology cases (Jolly and Raven, 2015; Konrad et al., 2012; Musiolik and Markard, 2011; Rosenbloom et al., 2016). Even in those cases, meaningful cooperation for institutional change is already challenging. However, organizing meaningful collective action in multi- innovation cases is likely to be even more challenging. Due to the variety of niche actors, there may also be a variety of visions of the future and proposals for socio-technical solutions to realize them. In such complex settings, it is unlikely that large numbers of actors will converge by default towards a single more sustainable vision of the future. We hypothesize that actors' visions of the future in multi-innovation cases are likely to be even more fragmented than in single innovation cases, due to the divergent set of solutions and visions proposed by regime challengers. Under such conditions, it is unlikely that a clear-cut and cohesive coalition will emerge by default. Rather, the emergence of powerful and coherent coalitions in sustainability transitions should be understood as the result of substantial efforts on the part of potential coalition members. Despite fragmentation and variety, this does not mean that the emergence of large and powerful coalitions is not possible in multi-technology cases. Several empirical studies, such as those conducted on the German low-carbon electricity transition, have shown that even in multi-innovation cases, eventually a large and powerful coalition can emerge (Dewald and Truffer, 2011, 2012; Jacobsson and Lauber, 2006).

Interaction of technical solutions

To assess (dis)similarities of visions, we introduce the notion of solution space. A solution space is a virtual space that embodies the set of articulated visions that may guide a sustainability transition. Several dimensions can be identified in such a solution space. Visions may overlap or differ for each of these dimensions. When visions overlap on more dimension, they are more similar than when they overlap on fewer dimensions.

Depending on the complexity of a socio-technical system, the number of dimensions may vary. For example, for the mobility transition, relevant dimensions may be related to public versus private transport or to the type of fuel and infrastructure used for mobility. Although actors might agree on some dimensions, they will be in competition if they diverge on other relevant dimensions of the solution space. For example, niche actors that support electric mobility are in symbiosis with those that support cars running on biofuels, since both groups of actors envision future mobility based on individual mobility. Conversely, e-car advocates are in competition with biofuel supporters when it comes to the fuel dimension. We suggest that actors who align on many dimensions are in close proximity to one another in the solution space. We hypothesize that if actors are close together in the solution space, they will be inclined to cooperate. Consequently, we also hypothesize that actors who do not share many relevant dimensions are more distant from each other in the solution space and therefore less inclined to cooperate.

The central hypothesis of this paper is that the probability of cooperation between actors or actor groups depends on their alignment regarding (technical) dimensions in the solution space. When many actors share the same relevant dimensions, coalitions can emerge. If this hypothesis is supported, it will in turn support reasons to believe that visions can be used to predict cooperation and coalition building.

Technical dimensions as a predictor of cooperation

To test if visions can be used as predictors for cooperation and coalitions building, visions need to be made measurable. To do so we suggest that relevant dimensions of how visions differ need to be determined. Since visions are likely to be very contextual to each socio-technical system, we suggest that on way to determine of relevant dimensions can be achieved in-depth interviews. Once relevant dimensions have been determined a solutions space can be constructed and visions of the group to be analyzed can be collected and classified according to these dimensions and solution space. To test if visions can function as predictors for coordinated behavior, the distance between them needs to be determined. This can be done by conducting a hierarchical cluster analysis. In a hierarchical cluster analysis, structural (dis)similarities among actors can be employed to analyze and visualize the distance between envisioned futures. The calculation of hierarchical clusters based on structural (dis)similarities is a well-known process in the analysis of networks (Wasserman 1994) and frequently applied in the study of advocacy coalitions (e.g., Leifeld, 2013). The results of hierarchical cluster analyses can be displayed in the form of a dendrogram (see Figure 8 for an example). Dendrograms are read from the bottom upwards. When interpreting a dendrogram, the agglomeration height at which any two or more actors are connected is important. The agglomeration height depicts how (dis)similar two

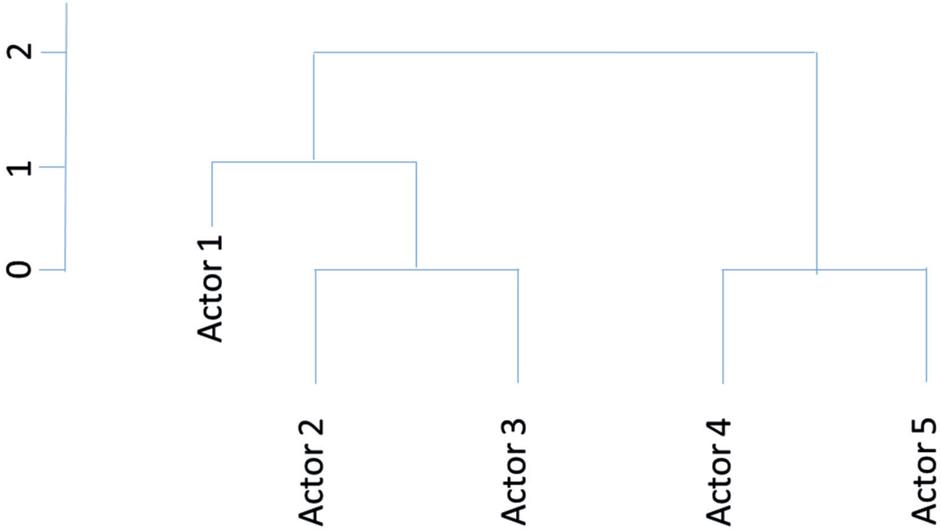

Figure 8: Exemplary dendrogram

groups are. In our case, the agglomeration height shows how similar the futures are that the actors envision. Actors who are connected at the highest height have a dissimilarity score of 0, meaning that they agree on all dimensions and that the futures they envision are congruent. In other words, the lower the difference in height, the closer the visions; the greater the difference in height, the more the visions diverge. For example, in Figure 8, industry (Actor) associations 2 and 3 are structurally equivalent because they have a dissimilarity score of 0. This means that they align on all analyzed dimensions. Similarly, Actors 4 and 5 share all dimensions and are thus structurally equivalent. The higher the level that connects the actors, the more dissimilar they are concerning the envisioned futures. For example, Actor 1 does not share all dimensions with Actors 2 and 3. Actor 1 is only connected with Actors 2 and 3 at the dissimilarity level 1. However, at a dissimilarity level >1, Actors 1, 2 and 3 can be denoted as a cluster and Actors 4 and 5 form a second cluster, since the futures that they envision are closer to each other than to the respective futures of the other cluster. Dendrograms are helpful for revealing similarities among actors. However, as they show clusters, single dimensions that are shared between actors located in different clusters may be omitted and remain invisible.

4.3 Methods

We conducted a coalition formation study of the German residential heat sector. Since this sector has substantial greenhouse gas emissions, the problem is how to change established institutions in ways that substantially reduce such emissions. We chose industry associations as focus actors because they "play an especially important role in the competition over institutions" (Jacobsson and Bergek, 2004, p. 822) in transition contexts. Furthermore, we argue that it is sensible to use industry associations as focal groups for the following reasons: (1) they have a clear message and can therefore function as signposts for actors to gather and meet; (2) they have the funds to organize meetings of coalition members, and are therefore likely to act as hubs for coalition building; (3) they are likely to be well connected in the heat sector and involved in political processes. Furthermore, because they represent specific technologies, they allow for a good overview of where visions of the future overlap and where they differ.

In our study, all 22 industry associations in the German domestic heat system were contacted in the fall of 2018 (Table 9).[18] They were identified based on desk-research and four pre-interviews with two German energy system researchers and two representatives of industry associations. Of the 22 industry associations, representatives of 16 associations agreed to be interviewed. Of the 16 associations, 7 promote renewable energy sources, 6 promote insulation materials, and 3 promote either a more efficient use of fossil fuels or fuel switching options (Table 9).

The interviews consisted of two parts. The first part was semi-structured and included questions on how the interviewees comprehended and envisioned the residential heat transition in Germany. We chose such an inductive approach to determine visions and their specific dimensions, since the literature has - to the best of our knowledge - not produced a set of clear dimensions that structure visions that we could incorporate.

In the second part of the interviews, each of the 16 interviewed representatives was given a list of all the other industry associations in the domestic heating system.[19] For each of the industry

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[18] In spring 2019, a new industry association was established that promotes thermal insulation materials made from renewable sources. It was not included because it was only established after the data collection was completed.

[19] This list also included three industry associations that did not agree to be interviewed. However, since several of the other interviewed partners indicated cooperation with those actors, they were kept in the data set to provide a more comprehensive picture.

associations on the list, the interviewee was asked whether the organization was unknown (1), known (2), there was interaction (3), or there was cooperation (4) (four levels). The scale is disjunctive while ascending, which means that the higher level includes the lower level. For example, if the representative of an organization stated that their organization interacted with another (3rd level), it could be assumed that the two organizations also knew each other (2nd level). Cooperation was defined as at least one joint activity over the last two years, such as a press release or a press conference. Interaction was defined as at least one jointly attended meeting over the last two years.

A two-step approach was used to test whether technology characteristics that shape visions of the future could predict cooperation among industry associations and therefore provide indications of coalition-building behavior.

First, by choosing a semi-structured interview approach we mapped the futures envisioned by principal actors in the German residential heat sector. The interviews were transcribed and labelled by using the MAXQDA-software.

First, we mapped the futures envisioned by principal actors in the German residential heat sector by transcribing and labelling the interviews with MAXQDA. In order to achieve intercoder reliability, the interviews were coded independently by the first author and by a research assistant at Fraunhofer ISI. Differences were reviewed, analyzed and mutually resolved. Based on the mapping process, we deduced relevant technology-related dimensions[20] that create the solution space for a low-carbon heat system in Germany. The data were used to compile a dendrogram, which was generated in “R” (statistical computing and graphic generation software). Based on the dendrogram, expectations were formulated concerning the cooperation behavior of the industry associations.

In the second step, we plotted the cooperation behavior of the interviewed representatives of the industry associations to discover whether the outlined expectations had materialized. Cooperation network data were collected to plot the cooperation behavior of the residential

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[20] In the theory section of this paper, we consistently refer to “dimensions.” We suggest that the ways transitions unfold can be envisioned based on technical and non-technical dimensions. In the study on which this paper is based, we analyzed the cooperation behavior of technology-related industry associations. Accordingly, in the remaining part of this paper, we focus on technical dimensions.

heat-related industry associations. Even though data for all four levels were collected, we only plotted cooperation data, since interaction between actors or the sole knowledge of another actor is unlikely to foster institutional change. Jointly attended meetings did not count as cooperation, since industry association representatives often attend the same gatherings, but do so to issue political statements and not necessarily to organize collective action. The software Visone (Brandes and Wagner, 2004, 2013) was used to calculate and visualize network data.

Table 10: Overview of interviewees[21]

Industry associations	Position
#1 Pellets	Managing director
#2 Biodiesel	Policy advisor
#3 Biogas	Managing director
#4 Biomass	Managing director
#5 Geothermal	Managing director
#6 Solar	Policy advisor
#7 Heat pumps	Policy advisor
#8 Umbrella group—insulation materials	Managing director
#9 Umbrella group—energy efficiency	Managing director
#10 Mineral wool	Managing director
#11 Extruded polystyrene foam	Managing director
#12 Polyurethane foam	Managing director
#13 Insulation installation systems	Managing director
#14 Natural gas	Managing director
#15 Combine heat and power	Managing director
#16 Large heat grids	Vice-president policy

4.4 Coalition building in the German domestic heat sector

In this section we present and analyze the empirical data. First, we introduce the interviewees' visions of how the heat transition could evolve. Thereafter, we describe how, based on the visions, we derived seven technical dimensions that establish the solution space for visions of the German domestic heat transition. The dimensions were used to perform a hierarchical cluster

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[21] Interview requests were also sent to the umbrella industry association for heating and gas furnaces, and to the federal association of energy and water management. There was no response to the interview requests. All other interviews were conducted in the fall of 2018.

analysis to predict the cooperation behavior of the analyzed industry associations. In turn, the predictions were compared with the collected social network data on the cooperation of the analyzed industry associations.

Visions of the German heat transition

The interview data suggest that the interviewed representatives' visions of how Germany's domestic heating sector should change differed substantially. Some actors envisioned the heat transition as mainly driven by the diffusion of renewable-based technologies and the reduction of heat demand due to insulation. For instance, the managing director of the geothermal industry association stated:

> The heat transition for me is a complete change to the energy supply in the built environment. This includes the use of all now known and applicable technologies. So, it's not about geothermal only. But it is really about a complete rethinking of how buildings are supplied with renewable heat and that they are well insulated.[22] (ID #5)

Other actors envisioned the transition as based mainly on the efficient use of fossil fuels, with less attention paid to renewables or the use of insulation materials. For instance, the managing director of the natural gas industry association outlined the following approach for the domestic heat transition:

> Yes, of course, CO2 is produced when gas is burned, but substantially less is emitted compared to burning heating oil or coal. [. . .] Using more gas will certainly carry us a good distance towards the climate targets, especially because the fuel switch to gas is usually also the most cost-effective route. Insulation is always more expensive and the introduction of renewable energy is even more expensive. It is important to reach a low-carbon system. However, we should always start with the low-hanging fruits. (ID #14)

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[22] Own translation

Translating visions into technical dimensions

We identified seven technical dimensions in the data that could be used to differentiate the interviewees' visions. The dimensions create the solution space for how the heat transition could evolve. Four of the dimensions are directly related to how CO2 emissions can be reduced:

1. Reduce CO2 emissions by insulating buildings to lower their energy demand.
2. Reduce CO2 emissions by installing renewable heat technologies.
3. Reduce CO2 emissions by supplying buildings with technologies that are not yet available and that run on renewable fuels that are not yet available.
4. Reduce CO2 emissions by replacing the current fossil-based heating infrastructures with more efficient fossil-based heating infrastructures.

The other three dimensions do not relate directly to the reduction of CO2 emissions, but to the scope of the infrastructure:

5. Heat supply takes place at the level of individual buildings.
6. Heat supply is based on gaseous energy sources and requires gas networks.
7. Heat supply is based on heat networks.

Quotes from the interviewees concerning the seven dimensions are listed in Table 10. Each of the 16 interviews were coded and analyzed with regard to the dimensions and the results are presented in Table 11. An actor scored "1" on a dimension if that dimension appeared in his/her vision and "0" otherwise.

Table 11: Technical dimensions and related quotes

Technical dimensions	Related quote
Technical dimensions related to emissions reductions	
1. Reduce CO2 emissions by insulating buildings to lower their energy demand.	That is why for us, it is always efficiency first. We say the building must first be insulated to keep the heat inside. No matter where I get the heat from at the end. From the sun or anything else." (ID #13)
2. Reduce CO2 emissions by installing renewable heat technologies.	"For me, the heat transition means the gradual conversion of the heat supply to renewable energies." (ID #5)
3. Reduce CO2 emissions by supplying buildings with technologies that are not yet available and that run on renewable fuels that are not yet available.	"If I then look into the future, after 2030, then technologies such as power-to-gas or power-to-liquid will also be suitable for the mass market. This means that we will be able to offer competitive synthetic methane or synthetic liquid fuels produced from renewable electricity." (ID #15)
4. Reduce CO2 emissions by replacing the current fossil-based heating infrastructures with more efficient fossil-based heating infrastructures.	"We have a built-in CO2 advantage with gas: switching from oil to gas saves 20, 30, 40 percent CO2. This perspective on fuel switching drives us forward. Yes, of course, CO2 is produced when gas is burned, but it is significantly less than if you burn oil or coal. Of course, we want to explore this advantage very clearly. It will certainly also help us to make good progress towards our climate targets." (ID #14)
Technical dimensions related to the scope of infrastructure	
5. Heat supply takes place at the level of individual buildings.	"Pellets are highly efficient. They have super CO2 saving factors and they are cheap. [. . .] And when you implement them in single-family homes, as we want to, then you can save ten tons of CO2 per building." (ID #1)
6. Heat supply is based on gaseous energy sources and requires gas networks.	"So the energy system of the future will be renewable plus gas, in all its facets, and the gas must of course also become green." (ID #14)
7. Heat supply is based on heat networks.	"The overall trend, in my opinion, are these heating grids 4.0, where different technologies can feed in at different temperature levels, including geothermal energy." (ID #5)

Table 12: Technical dimensions and actors in Germany's domestic heat system

	Dimensions related to emissions reductions				Dimensions related to the scope of infrastructure		
	Dimension 1	**Dimension 2**	**Dimension 3**	**Dimension 4**	**Dimension 5**	**Dimension 6**	**Dimension 7**
	Reduce CO2 emissions by insulating buildings to lower their energy demand	**Reduce CO2 emissions by installing renewable heat technologies**	**Reduce CO2 emissions by supplying buildings with technologies that are not yet available and that run on renewable fuels that are not yet available**	**Reduce CO2 emissions by replacing the current fossil-based heating infrastructures with more efficient fossil-based heating infrastructures.**	**Heat supply takes place at the level of individual buildings**	**Heat supply is based on gaseous energy sources and requires gas networks**	**Heat supply is based on heat networks**
Pellets	0	1	0	0	1	0	0
Biodiesel	0	1	0	0	1	0	0
Biogas	0	1	0	0	0	1	1
Biomass	0	1	0	0	1	1	1
Geothermal	1	1	0	0	1	0	1
Solar	1	1	0	0	1	1	1
Heat pumps	1	1	0	0	1	0	0
Umbrella—building envelope	1	0	0	0	0	0	0
Umbrella — energy efficiency	1	0	0	1	0	0	0
Mineral wool	1	0	0	0	0	0	0
Extruded polystyrene foam	1	0	0	0	0	0	0
Polyurethane foam	1	0	0	0	0	0	0
Insulation installation systems	1	0	0	0	0	0	0
Large heat grids	0	0	1	1	0	0	1
Natural gas	0	0	1	1	1	1	0
Natural gas cogeneration	0	0	1	1	1	1	1

Hierarchical clustering of technical dimensions

To discover which actors align along the seven technical dimensions and are therefore in close proximity in the solution space, we conducted a hierarchical cluster analysis based on the data presented in Table 11. The results are illustrated in the dendrogram in Figure 9. In the dendrogram, actors whose visions were very similar are displayed as members of clusters and subclusters. If the hypothesis developed in the theory section holds (i.e., that actors who share similar visions of the future are inclined to cooperate), the clusters displayed in the dendrogram should predict cooperation patterns.

The dendrogram (Figure 9) shows that the industry associations are split into two clusters at a score of 2. Cluster A encompasses all 13 industry associations that envision the heat transition as either driven by lowering the energy demand of buildings (dimension 1, indicated in blue) or by using the available renewable energy technologies (dimension 2, indicated in green). Cluster B encompasses three actors (red and orange), who envision a more efficient use of fossil fuels (dimension 4), and a substantial use of heat networks as well as gas networks (dimensions 6 and 7). All three actors in cluster B also think that heat demand will eventually be met by renewable energy sources. However, they believe this will only happen in the long term and mainly using fuels that are not yet available on a large scale (dimension 3).

Since cluster B encompasses only three industry associations and cluster A encompasses 13 industry associations, we analyze cluster A in more detail, as follows. At a score of about 1.7, cluster A is divided into two subclusters.

Subcluster A1 encompasses all the actors who envision the heat transition as mainly driven by reducing heat demand (blue). All six actors in this subcluster promote insulation materials. In the interviews, five of these six representatives focused solely on the dimension of reducing heat demand (dimension 1). Since those five did not mention any of the other six dimensions, the associations the presented are all structurally equivalent and therefore feature a dissimilarity score of 0. The umbrella group for energy efficiency also envisions the heat transition as based on reducing the heat demand of buildings by diffusing insulation materials. However, since it sees efficiency as a general goal, it also regards the use of efficient fossil fuel infrastructure as a viable option to reduce carbon emissions (dimension 4). For this reason, it is not structurally equivalent to the other five industry associations that promote insulation materials.

Subcluster A2 encompasses all industry associations that envision the heat transition as mainly driven by renewable fuels (dimension 2, green). It encompasses all actors who promote available renewable heat technologies. Even though they all agree on the general trajectory, the dendrogram shows that their visions are more fragmented than the visions of the actors in subcluster A1. Therefore, at a score of 1.5, cluster A2 is again divided into two subclusters. Subcluster A2A encompasses industry associations that envision the heat transition as driven by individual-building heating systems (dimension 5). These are industry associations that promote the use of heat pumps, pellets and biodiesel. By contrast, subcluster A2B encompasses actors whose visions of the heat transition include gas infrastructure and/or heat networks (respectively dimensions 6 and dimension 7). These are the biogas industry association, the biomass industry association, the geothermal industry association, and the solar industry association.

When comparing the structure of subclusters A1 and A2, it is apparent that cluster A1 is substantially less fragmented than cluster A2. For example, in cluster A1, five of six industry associations are completely aligned concerning their prioritized technological dimensions. By contrast, in subcluster A2B only two groups have a dissimilarity score of 0. None of the other industry associations are completely aligned.

In the theory section of this paper, we have hypothesized that actors in close proximity to each other in the solution space will be more inclined to cooperate than actors who are farther apart. Based on this hypothesis and the data displayed in the dendrogram, we expect cooperation between the actors in clusters A1, A2 and B. This should become visible in the cooperation network presented in the next section. Furthermore, we expect that the cooperation density between the actors in cluster A1 is higher than the cooperation density between the actors in cluster A2. This is due to the higher fragmentation in subcluster A2 than in subcluster A1.

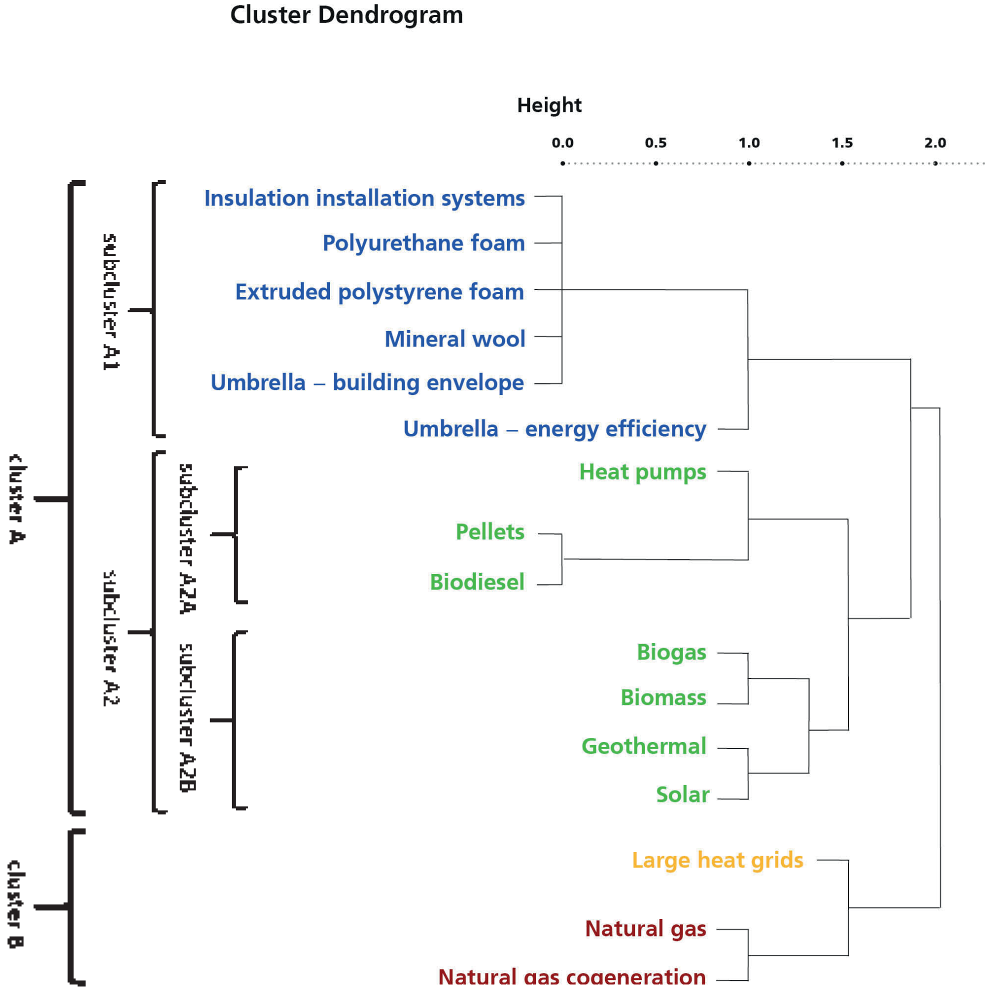

Figure 9: Dendrogram based on hierarchical clustering of industry associations' vision dimensions

Cooperation clusters among industry associations

Figure 10 shows the cooperation network among the analyzed technology industry associations. The network is based on network data that was collected as part of the interviews. In the network, cooperation is indicated by black links in cases when interviewees stated that they cooperate with each other. A grey link indicates that only one representative of an industry association claimed a cooperative relation existed. Industry associations that promote a single technology are represented by a circle, whereas umbrella industry associations are shown as squares. The coloring of the industry associations is the same as in the dendrogram. Industry associations that belong to cluster A1 (insulation materials; dimension 1) are depicted in blue. Industry associations that belong to cluster A2 (renewable energy; dimension 2) are depicted in green. Industry associations that belong to cluster B (efficient fossil fuel, gas grid, heat grid and long-term renewable infrastructure; dimensions 3, 4, 6, and 7) are depicted in orange and red, respectively.

Analysis of the industry associations' cooperation behavior revealed the cooperation structures predicted in the previous subsection. First, we expected that clusters A1, A2 and B depicted in the dendrogram would become visible in the cooperation network. As expected, the main clusters A (A1 blue, A2 green) and B (red/orange) are clearly visible in Figure 10. Actors in cluster A1 appear on the left side of the cooperation network. Actors in cluster A2 congregate in the top-right corner and actors in cluster B are located in the bottom-right of the cooperation network.

Furthermore, we expected the cooperation density between actors in cluster A1 to be higher than the cooperation density between actors in cluster A2, because the visions of the actors in cluster A1 were more aligned than the visions of the actors in A2. The cooperation network confirms this expectation. While cluster A1 features a cooperation density of 83.3%, cluster A2 features a cooperation density of 48%.[23]

Based on the vision-derived hierarchical clustering, we were able to predict the general coalition building structures shown in Figure 10. However, the cooperation network shows one cooperative anomaly that could not be predicted. For example, the solar industry association aligns with the biodiesel industry association on more dimensions (four dimensions: 2, 3, 4, and 5) than it aligns with the natural gas industry association (two dimensions: 5 and 6) (see the data in Table 11). However, the solar industry association cooperates with the natural gas industry association and does not cooperate with the biodiesel industry association. This finding suggests

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[23] The cooperation network shown in Figure 10 is a binary network. The density of such a binary network is calculated by dividing the total number of realized ties by the total number of possible ties. In cluster A1, 25 of 30 possible links were realized (83.3%). In cluster A2, 20 of 42 possible links were realized (47.6%). Since cluster B only encompassed three industry associations, we did not calculate the cooperation density for this cluster.

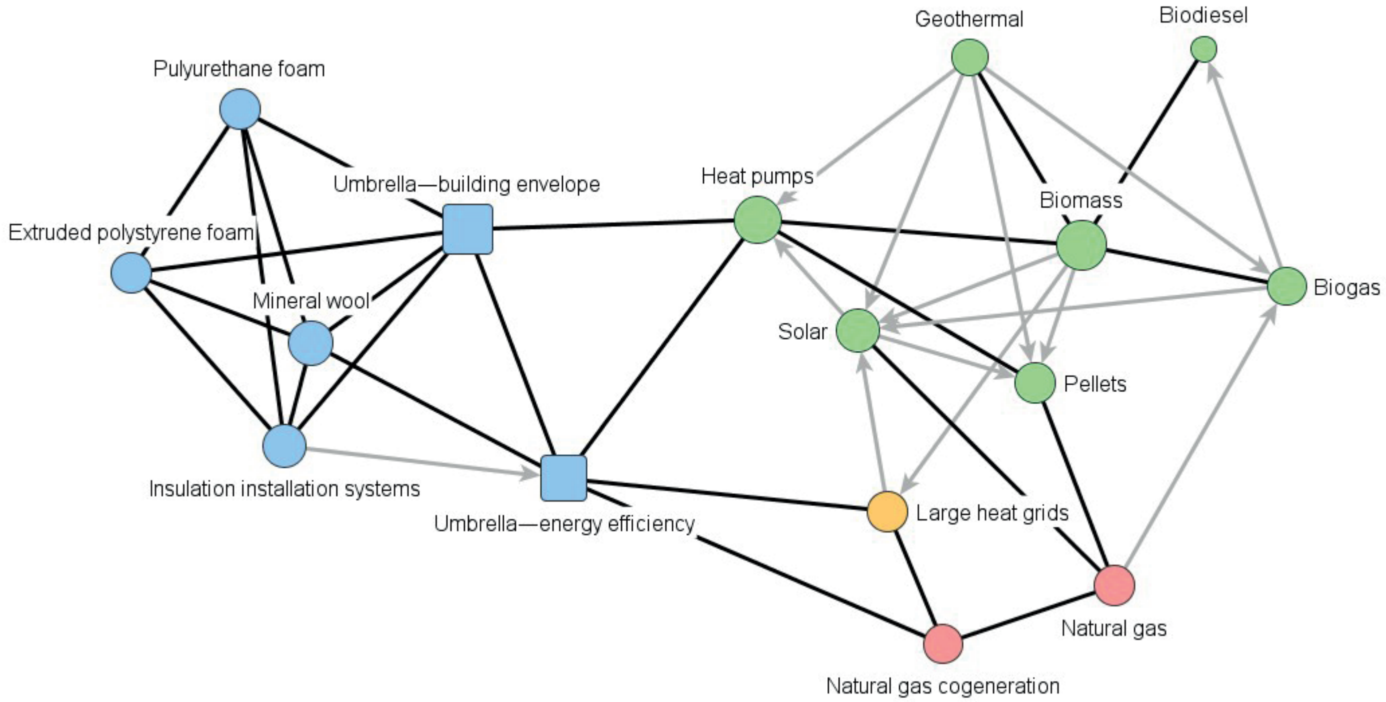

Figure 10: Cooperation among technology industry associations in the German domestic heat sector

that the proximity of visions of the future is only one indicator to predict cooperative behavior, but that it is possible that some vision dimensions are more important than others, for example when technologies are specifically complementary to each other such as gas boilers and solar thermal heat panels that in Germany are often deployed together. Another explanation could be that it is possible that other reasons not covered in this study are also influential when it comes to influencing cooperative behavior.

4.5 Implications

The results of our analysis show that the German heating sector features a variety of technical solutions as well as a variety of actors. The results also provide evidence in support of our main hypothesis, namely that industry associations cooperate with other industry associations based on shared visions of the future. These visions are substantially shaped by the technology characteristics. Arguably most of the ties between the analyzed actor groups are likely to have been predictable based on the different industries that the respondents represent, and their material interests. However, if predictions would have been based only on actor's direct material interests, then it would have been expectable that the biogas and the natural gas group, as well as the large heat grids and geothermal group would have indicated reciprocal cooperation, since these groups have shared material interests. The biogas group and the natural gas group both require gas grids for their operations, and the large heat grids group and the geothermal group have complementary material interests, since industrial size geothermal applications require large heat grid. Since these groups did not show reciprocal cooperation, it can be assumed, that using visions as proxies for cooperation is more insightful then solely relying on material interests.

Next to the confirmed hypothesis that actors coordinate their action based on their visions of the future, we furthermore hypothesized that coalitions can emerge when many actors share the same relevant dimensions. This, too, can be confirmed, as all three clusters indicated in the dendrogram appeared in the cooperation network.

Even though the analysis included only technology industry associations, the groups showed substantial diversity in their visions concerning the transition of the German heating sector. This is likely to be typical of transitions, due to the wide range of potential transition pathways that are supported by diverse groups of actors. Also this diversity can potentially be seen as a result of the fragmented nature of the German heat system (Wesche et al., 2019).

From the transitions literature, we know that a clear vision to which relevant actors can relate is necessary in order to accelerate a sustainability transition. For instance, Loorbach (2007, p. 11) states that transitions “need to be based on a shared sense of urgency, on forceful and inspiring long-term sustainability visions and on societal innovation strategies.” Similarly, Hekkert et al. implicitly consider visions as instruments of “priority setting and thus [defining] the direction of technological change” (Hekkert, Suurs et al., 2007, p. 423).

If actors advocate a sustainability transition and converge to form a large coalition, they are more likely to concentrate sufficient power to influence the institutional change process. The findings from our study show that is not always the case that such a large coalition fill form. Our case shows that a plethora of visions that deviate concerning specific traits is likely to exist in transition contexts. Such a plethora of visions is counterproductive to the emergence of a single vision that can unite a sufficient number of actors who can then develop the force needed to bring about institutional change. In our study, it is the case that a single strong vision does not emerge due to the variety of visions. We have shown that the analyzed industry associations are capable of cooperating and building coalitions. However, these seem too small and too focused at present to be able to bring about institutional change and push for a policy change. Hence, the fragmentation of the actor landscape is perpetuating the current institutional lock-in. To escape the lock-in, we suggest that actors become or institutionalize coalition brokers that explicitly look for overlaps of visions and use them to forge more encompassing and powerful coalitions. Here their main task would be to balance “between multiple priorities, interests and knowledge pools for creating a shared vision and activities to facilitate transitions” (Kivimaa et al., 2019, p. 1067).

Furthermore, our data revealed that not only is the coordination among niche-related industry associations (i.e., those promoting genuinely more sustainable products) underdeveloped, but also that these niche technology industry associations sometimes cooperate with incumbent industry associations for opportunistic reasons. This is the case, even though these incumbent technology industry associations promote heat technologies that clearly contribute to climate change. This cooperation between niche and incumbent actors is in line with the notion mentioned in the theory section: actors cooperate based on (technology-specific) visions of the future. If two solutions are aligned on important dimensions, it may lead to cooperation between industry associations, even if they envision very different end states of the transition (e.g., low- carbon versus fossil-fuel based). With regard to the overall transition, cooperation between niche actors and incumbent actors is not necessarily helpful; rather, it is likely to undermine the emergence of a forceful pro-sustainability coalition.

4.6 Conclusions

The research question addressed in this paper is: "How do the similarities of visions regarding desired end states of sustainability transitions determine the cooperation between actors supporting different emerging socio-technical configurations?" In answering this question, we have aimed to contribute to a better understanding of what determines cooperation and the emergence of advocacy coalitions in transitions.

Based on our study, we have shown that a wide range of technologies exists in the German heating sector. Each of these technologies is represented and promoted by different industry associations. The actors in these associations have visions of the end state to which they aspire. The large variety of technologies is reflected in a multitude of visions, which leads to a fragmented cooperation landscape. The study findings shows that vision similarities regarding desired end states of sustainability transitions may help to predict main cooperation clusters. We have also shown that technology characteristics are a key determinant of these visions of the future.

Cooperation between niche interest groups is based on technological symbiosis along specific dimensions. In our case, a large cohesive pro-transition coalition that unites all pro-sustainability niche interest groups did not emerge. The formation of such a cohesive coalition is undermined by continued cooperation between low-carbon niche industry associations and incumbent fossil fuel industry associations. The lack of a strong low- carbon coalition is likely to be contributing to the perpetuation of the institutional and political lock-in. As a result, a low-carbon heat transition continues to be stalled. We suggest that, for strong, powerful, and cohesive low-carbon coalitions to emerge, actors supporting low-carbon solutions and policy entrepreneurs need to find a common vision (or "shared ground") that can unite a wide variety of actors.

As the presented analysis represents a single case study, the robustness of the results could be improved by replicating it in other transitions settings. Furthermore, we only focused on the technological dimensions of envisioning a transition future, yet we are aware that actors may envision futures that are not necessarily based only on technological dimensions. The analysis is further limited by the number of interviewees. The results would have benefited from a fuller sample of industry associations. However, we are certain that 16 of our original 22 datasets were adequate to produce sufficiently reliable data from which to derive the scientific insights presented in this paper. Furthermore, in this paper, we have treated the interviews as representing the views of the respective organizations. This has some limitations and to obtain a more comprehensive assessment, ideally several more interviews per industry association would have been needed.

We see valuable avenues for further research on the emergence and maintenance of sustainability transitions related to coalitions. In particular, it would be interesting to learn how representatives of industry associations can engage in institutional work such as building visions that resonate with a variety of potential coalition members. Also, it would be of interest to learn about the obstacles that policy entrepreneurs face in transitions settings and how these can be overcome.

5

Accelerating sustainability transitions through coordination – a review of the advocacy coalition framework

5.1 Introduction

Sustainability transitions can be understood as the transformation of socio-technical systems towards a more sustainable provision of societal functions, such as energy or mobility. The innovations that can provide these functions in more sustainable ways often emerge in niches. These niches provide a protective space for innovations (Kemp et al., 1998; Smith and Raven, 2012). Initial protection is key, since especially radical innovations often cannot compete successfully in selection environments dominated by incumbent regime actors (Raven et al., 2012). If radical innovations are to develop beyond such niches and become competitive, the selection environment needs to be adapted. Policy change is a key precursor that initiates the adaptation of selection environments. Policy change that leads to an adaptation of the selection environment in ways that support radical innovations is often a prerequisite for mainstreaming such innovations.

In this paper, we suggest that policy change is largely attributable to the ways in which actors coordinate. More specifically, policy change is dependent on how successful actors coordinate and collectively exert pressure on government and policymakers for policy change.

The literature on socio-technical transitions highlights the role of coordination, often in connection with coalition building. For example, in a case study of offshore wind in the UK, Raven et al. (2016, p. 174) conclude that "a coalition of large business actors, public bodies and policy makers were successful in significantly shaping the selection environment to make it more amenable to offshore wind." Similar examples of the role of coordination in socio-technical transitions can be found in (Geels et al., 2016; Jacobsson and Bergek, 2004; Lauber and Metz, 2004; Ulmanen et al., 2009). However, even though the role of coordination and coalition building has been repeatedly emphasized, the influencing factors that lead to successful coordination in coalitions are not yet sufficiently understood.

Thus, the aim of this paper is first to contribute to a better understanding of the factors that influence coordination and second to highlight the implications to accelerating sustainability transitions. Accordingly, the research question of this paper is: *What determines successful coordination of actors in political processes?*

To answer the research question, the paper reviews a major framework that puts actors and their agency center stage: The Advocacy Coalition Framework (ACF). The ACF is based on the assumption that coordinated activity can influence the policy process (Sabatier and Jenkins-Smith, 1993) and in the ACF literature coordination is understood as a concept that encompasses the stability of coordination efforts, as well as defection from coordinated action.

There has been a substantial expansion of the ACF literature in recent years. This expansion includes two literature reviews (Pierce et al., 2017; Weible et al., 2009). However, so far, the ACF literature lacks a comprehensive review of what influences coordination in advocacy coalitions. By reviewing the ACF in terms of the factors that influence coordination, this paper contributes not only to the sustainability transitions literature, but also to the ACF literature.

The paper is structured as follows. First, we build on previous work to outline the key concepts of the sustainability transitions literature and the advocacy coalition framework. We then describe how we compiled the core corpus for this review. Thereafter, we present and summarize the findings about what influences the coordination of advocacy coalitions. Based on these findings, we highlight the implications of coordinating advocacy coalitions in socio-technical systems to accelerate sustainability transitions, and present suggestions for how to form influential advocacy coalitions. We conclude with reflections on the research conducted and ideas for further research.

5.2 Theory

Coordination in sustainability transitions

Transitions are understood as far-reaching changes in socio-technical systems that are aimed at providing specific societal functions, such as mobility or energy services (Markard et al., 2012). Sustainability transitions can be understood as the transformation of socio-technical systems towards a sustainable provision of these societal functions. Novel socio-technical innovations that can contribute to a more sustainable provision of societal functions emerge in niches, where they are nurtured and protected from the current selection environment (Raven, 2005). Due to this protection and nurturing, incremental innovations may become competitive within unchanged selection environments (Smith and Raven, 2012). However, although the initial protection and nurturing in niches is vital, it may not be sufficient for radical innovations to thrive. For radical innovations to become competitive, the institutional selection environment usually needs to be adapted (Fuenfschilling and Truffer, 2014). Policy change is often seen as a key prerequisite for the adaptation of selection environments. In this paper, we assume that in democratic countries individuals acting alone rarely have the power needed to bring about policy change. Rather, individuals need to coordinate their actions with others who are supporting innovation in order for sufficient power to be acquired. The power can then be used to exert pressure on governments and eventually lead to the implementation of policies that change the selection environment.

The literature on socio-technical transitions repeatedly emphasizes the role of coordination. For example, in their seminal paper titled 'The governance of sustainable socio-technical transitions', Smith et al. (2005, p. 1492) state: "system-level change is, by definition, enacted through the coordination and steering of many actors and resources." Empirical examples of actor coordination that eventually lead to policy change can be found in published work by Lauber and Metz (2004), Jacobsson and Bergek (2004), Ulmanen et al. (2009), Raven et al. (2016), and Geels et al. (2016). In these contributions, coordination is consistently described as taking place in coalitions that collectively pressure regime actors to change policy and adapt the selection environment to favor niche innovations.

Even though the literature on socio-technical transitions repeatedly emphasizes the role of coordination and coalition building, it does not incorporate knowledge from other fields that specifically deal with coordination in coalitions, nor do any publications compile the impacts of coordination on policy change. For this reason. we turn to a body of literature that focuses specifically on the coordination of individuals and policy change by applying the Advocacy Coalition Framework (ACF). We draw on the ACF because it deals explicitly with coordination-driven policy change and offers a variety of insights into why and how actors coordinate, and how coordination is influenced by different contexts.

Although we acknowledge previous ACF-inspired work in the literature on socio- technical transitions (Gomel and Rogge, 2020; Haukkala, 2017; Markard, Suter, Ingold, 2015; Ulmanen et al., 2015), we still see a substantial gap in the literature with regard to how coordination-related insights from policy process theories such as the ACF can inform transitions theory.

The Advocacy Coalition Framework

The ACF is "one of the most established and successful approaches for understanding policy processes across the globe" (Weible et al., 2019). It describes policy change as the result of coordination-driven coalitions that compete for dominance in a given policy subsystem (Jenkins-Smith and Sabatier, 1994; Sabatier, 1988, 1998). A policy subsystem can be understood as "the set of actors who are involved in dealing with a policy problem such as air pollution control, mental health, or energy" (Sabatier, 1988, p. 138). Policy subsystems can be defined at every political level, including global, supranational, national, and regional levels. The advocacy coalitions acting in these policy subsystems comprise policy actors that collectively "show a nontrivial degree of coordinated activity over time" (Sabatier and Jenkins-Smith, 1993, p. 25). Advocacy coalitions not only include traditional members of the policy iron triangle (members of parliament, bureaucrats and industrial interest groups), but also actors from very diverse backgrounds, such as researchers, journalists, representatives of political parties, think tanks, and grassroots citizen groups (Sabatier, 1988; Weible and Ingold, 2018). These can be individuals who act autonomously, or individuals who represent collective bodies such as interest groups, companies or other types of organizations. These actors coordinate by applying a "spectrum of activity in which one party alters its own political strategies to accommodate the activity of others in pursuit of similar goals" (Zafonte and Sabatier, 1998, p. 480). To influence the policy process, the actors require and use resources, which can include supportive members of the public, stable allies, access to elected officials and those in position of authority, funds, scientific and technical information, and leadership (Weible et al., 2019).

Early versions of the ACF suggested that actors are attracted to join the same coalition and coordinate due to mutually overlapping beliefs (Jenkins-Smith and Sabatier, 1994). For this reason, authors focusing on the AFC developed a detailed belief system hierarchy that guides individuals to engage in coordination. The hierarchy encompasses three levels of beliefs: deep core beliefs, policy core beliefs, and secondary beliefs. Deep core beliefs are fundamental normative values and ontological axioms. They are not policy- specific and therefore may apply to multiple policy subsystems (Jenkins-Smith et al., 2017). Policy core beliefs are bound by scope and topic to the policy subsystem and thus have territorial and topical components. Normatively, policy core beliefs may reflect basic orientation and value priorities for the policy subsystem (Jenkins-Smith et al., 2017). Empirically, policy core beliefs include overall assessments of the seriousness of the problem, its main causes, and preferred solutions for addressing it (Jenkins-Smith et al., 2017). Lastly, secondary beliefs deal with “the specific instrumental means for achieving the desired outcomes outlined in the policy core beliefs” Jenkins-Smith et al. (2017, p. 141).

When used for theoretical enquiry, the ACF has three general theoretical focal points: advocacy coalitions, policy change, and policy-oriented learning (Pierce et al., 2017, 15). In this review, we focus on advocacy coalitions. Specifically, we are interested in what determines successful coordination of actors in political processes.

In the ACF the principal explanation for coordination is the overlap or coherence of belief systems (Sabatier, 1988). While overlapping belief systems are still considered one of the major drivers of coordination (Weible et al., 2019), a variety of other factors that support or inhibit coordination have been described. These include, among others, power seeking (Henry, 2011), access to expertise (Calanni et al., 2015), the availability of brokers (Henry et al., 2011), and the level of contestation (controversy) in a policy subsystem (Weible et al., 2018).

Although, to date, ACF research on coordination has concentrated on the reasons that lead to coordination, a sole focus on coordination neglects the fact that engaging in coalitions is a process that evolves over time and that coalition members can also be tempted to leave a coalition before the envisioned policy change is implemented (Sabatier, 1998; Schlager, 1995; Zafonte and Sabatier, 2004). This is why there is an inextricable link between coordination and the stability of coalitions, as well as defections from coalitions. For this reason, in this review we not only compile and review the reasons that lead to the coordination of actors, but also the reasons that contribute to the stability of coalitions or the defection of actors from coalitions. The next section describes the literature review method used, which builds on the three themes of coordination, stability and defection that are covered.

5.3 Method

Creation of corpus

Our first step towards a better understanding of coordination among actors in coalitions was to compile a comprehensive corpus of peer-reviewed journal papers. We used the Web of Science database and the Scopus database to generate a list of journal papers (June 2020). We used both databases, as they are congruent to a large extent, but each still exclusively lists certain publications. To be eligible for inclusion in our corpus, journal papers had to be written in English, peer reviewed, and mention the term "advocacy coalition" in the title, abstract or keywords. Since Sabatier published the first paper on the Advocacy Coalition Framework in 1988, only papers published between 1988 and June 2020 were eligible for inclusion. The search term produced 618 hits in the Web of Science database and 590 hits in the Scopus database. To obtain clean data, we eliminated duplicates and matched the titles of the papers from the two databases by calculating Levenshtein distances (Levenshtein, 1966) using R software. The Levenshtein distance between two strings is defined as the minimum number of insert, delete and replace operations to convert the first string to the second. Based on Levenshtein distance calculations (maximum of 10 single-character edits), the R software generated a single corpus of 742 documents.

Reduction of corpus

To produce a corpus of papers that included only papers dealing with the coordination of advocacy coalitions, we screened the titles, abstracts and keyword of all 742 papers. Furthermore, we used a basic text mining approach to improve the decision on whether to include a paper in the reduced corpus. Additionally, the method screened each of the 742 papers for how many hits they had regarding the following three terms: coordination, collaboration, and cooperation. We not only mined for coordination, but also for collaboration and cooperation, since these two terms also indicate coordinated behavior and are used interchangeably with the term "coordination" by some ACF contributing authors. Following the screening process, all papers in the initial corpus were classified in two main categories. The first category included all papers that dealt in depth with the ACF, while the second category included all papers that only referenced the ACF or that did not refer to the ACF but used the combination *advocacy* and *coalitions* by coincidence in the title, abstract, or keywords. We focused on the first category to answer our research question. The category included 55 papers, which formed the initial core corpus.

Analysis of the core corpus

The first step in our analysis was a thorough reading of each of the 55 papers. During the reading process, it became clear that 19 papers do not deal with topics related to the research question and therefore they were removed from the core corpus. For example, some dealt with the stability of policies rather than the stability of coalitions. Other papers merely used the ACF to make sense of the empirically analyzed case and did not derive any theoretical insights of relevance for our research. The corpus then comprised 36 journal papers. During the analysis, four additional papers were discovered by following citations in the initial core corpus. The four papers, which were added to the corpus, met the criteria for the selection process, but do not mention the term "advocacy coalition" in their title, abstract, or keywords. Furthermore, a seminal book that deals with some core concepts for the first time in the literature (Sabatier and Jenkins-Smith, 1993), as well as a conceptual book chapter concerning coordination, which was repeatedly cross-referenced in the corpus (Jenkins-Smith et al., 2014), and another empirical book chapter (Nohrstedt and Olofsson, 2016) were all added to the core corpus. As a result, the final core corpus comprised 43 papers (Figure 11 and Appendix B).

Of these 43 papers, 6 are of a conceptual nature and another 4 are literature reviews (see Appendix B). The remaining 33 papers are empirical studies which illustrate how widespread the Advocacy Coalition Framework has become over the last three decades. Of these 33 papers, 11 deal with regional policy issues, four with policy issues at USA state level, 16 with policy issues at national level, and 2 with policy issues at a supranational level. Furthermore, the 33 papers cover 17 types of policy issues: marine and water policy (8), climate policy (3), energy policy (3), fracking policy (3), carnivore management policy (2), forest policy (2), pharmacy and drug policy (2), water supply policy (2), automotive pollution control policy (1), foreign policy (1), higher education policy (1), land-use and transportation planning policy (1), regional planning policy (1), tobacco control policy (1), trade union policy (1), and workplace safety policy (1).[24] These issues were examined in seven countries: the USA (17), Sweden (6), Switzerland (5), UK (1), Mozambique (1), Canada (1), and Denmark (1). In the analysis section, a number of examples from the empirical studies are used to illustrate our theoretical findings.

All 43 papers in the final core corpus were read and assessed using MAXQDA qualitative data analysis software. The analysis was guided by a code tree encompassing all five terms relating to the coordination of advocacy coalitions: coordination, stability, defection, cooperation, and collaboration (see Appendix C).

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[24] One of the reviewed papers is based on 11 policy case studies (Fischer 2014). However, we have not included it in this paper because this large number risked inflating the calculations, thus leading to data ambiguity.

During the analysis, specific coordination-related topics emerged from the corpus. In order to discover whether these topics and keywords were salient throughout the final core corpus, we performed additional lexical searches for them. The lexical searches entailed basic counts of keywords that had emerged during the analysis of the papers in the corpus. If the search revealed topics and findings utilized or covered by several authors, those topics and understandings were integrated into the findings.

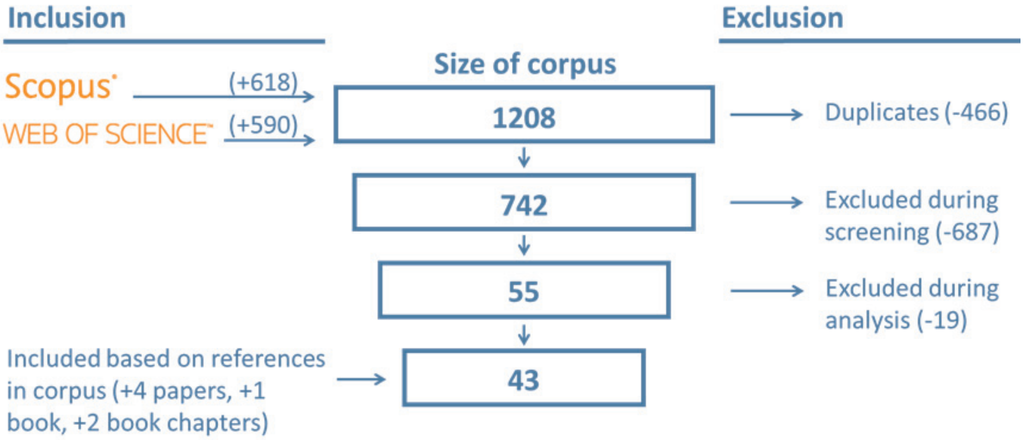

Figure 11: Compilation of corpus

5.4 What influences the coordination of advocacy coalitions?

In this section, we present the results of the analysis. The analysis revealed that coordination is analyzed on three distinct levels in applications of the ACF: the individual actors, the coalition, and the policy subsystem. In the following this results section is divided into three subsections that reflect the three levels.

Individual actors

The first subsection of the results section deals with individual actors. As well as the reasons for them to engage in coordination, we also look at defection and how coordination changes over time.

Reasons to coordinate

We begin by presenting four factors that the ACF literature views as influential for coordination: functional interdependencies, shared beliefs, resource dependency, and trust.

Creating contact: functional interdependencies and the role of internal brokers

Our first finding is that establishing contact between potential coalition partners is a basic prerequisite for coordination. The ACF literature suggests that organizations and individuals that are politically active in the same policy subsystem are bound to interact in order to cooperate or compete for political influence. However, demarcations of policy subsystems are not predefined and actors may not be aware of all other actors in the same policy subsystem (Henry et al., 2011, p. 429). This is further complicated by the fact that policy subsystems can span several geographical divisions from local policy subsystems to policy subsystems around the world. The papers that cover the different spans of policy subsystems include one by Matti and Sandström (2011), who look at carnivore management at local county level in northern Sweden, and one by Wray et al. (2017), who look at the global tobacco policy subsystem. Authors who refer to the AFC suggest that coalition brokers play a major role in establishing the initial contact between actors in a policy subsystem (Henry et al., 2011; Ingold and Fischer, 2014; Weible, 2008; Weible, Sabatier et al., 2011).

The concept of functional interdependencies suggests that policy actors interact when one of the following two prerequisites is satisfied: (1) their activities “are causally related to each other” (Fenger and Klok, 2001, p. 160); for natural interdependence see Zafonte and Sabatier (1998, p. 481), (2) they interact due to artificial interdependencies (Zafonte and Sabatier, 1998, p. 481) when “some external actor (e.g. the legislature) has linked their activities for some purposes of its own” (Fenger and Klok, 2001, p. 160).

The debate on the outer continental shelf oil and gas leasing that emerged in the USA at the end of the 1960s is an example of a frequently cited causal relationship (natural interdependence) (see (Fenger and Klok, 2001; Jenkins-Smith et al., 1991). After an oil spill off the coast of Santa Barbara, coastal residents and environmental groups began coordinating action against further oil drilling and leasing of exploitation rights. Before the oil spill, these groups had rarely interacted, but the oil spill was the cause that brought them together to coordinate their actions against a common opponent.

Calanni et al. (2015, p. 909) cite marine aquaculture partnerships as an example of artificial interdependence. The partnerships were "created through legislative mandate" to bring policy actors together "with the purpose of addressing concerns regarding fish health, public safety, and other issues relating to the expansion of the aquaculture industry" (Calanni et al., 2015, p. 909).

Additionally, initial contact can be established by internal coalition brokers,[25] who introduce actors to each other (Sabatier and Jenkins-Smith, 1993). Once coordination has been established, they "keep multiple actors working toward common goals" (Henry et al., 2011, p. 422; Sabatier and Jenkins-Smith, 1993) and function as "fixers" if conflicts arise (Sabatier and Jenkins-Smith, 1993). However, it is not very clear from the literature how and why actors take on the role of an internal coalition broker.

Shared beliefs

The ACF assumes that when actors become aware that they are active in the same policy subsystem, the *belief homophily hypothesis* will explain their coordination. The hypothesis suggests that overlapping beliefs act as the "principal glue" among coalition members (Sabatier, 1988, p. 141). Following this, it was assumed that coordination would increase with belief congruence, and that conflict would increase with belief divergence (Zafonte and Sabatier, 1998). Since deep core beliefs are not specific to a policy subsystem and secondary belief preferences may not last over long periods, it was suggested by Weible et al. (2009) and others that policy core beliefs are most important for predicting coordinated activity. Over the years, the belief homophily assumption has been repeatedly supported in a number of studies (Henry, 2011; Ingold and Fischer, 2014; Matti and Sandström, 2011, 2013; Nohrstedt and Olofsson, 2016; Weible, 2005; Weible and Sabatier, 2005; Zafonte and Sabatier, 1998).

However, following initial criticism by Schlager (1995) it became contested that similar core policy beliefs are the only reason for actors to coordinate. Schlager's key argument was that beliefs may have an influence, but do not suffice to explain coordinated behavior (Schlager, 1995). Instead, she called for a more adequate explanation of "why actors holding similar beliefs

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[25] Henry et al. 2011 use the term "policy brokers" to describe these persons. However, in this paper we use the term to describe brokers who negotiate policy agreements between several coalitions, and we use the term "internal policy brokers" to describe actors who facilitate coordination within one coalition.

form coalitions to collectively press their policy goals" (Schlager, 1995, p. 244). Over the last 30 years, most ACF-based studies have aimed to find further evidence that belief congruence is a direct predictor of coordinated action (see authors mentioned at the end of last paragraph), while in the last 10 years a number of analysts have taken up the challenge of finding out whether there are other factors that help to explain coordinated behavior. Going beyond the rather simple proposition that belief homophily alone drives coordination, efforts from these scholars have provided two essential insights.

First, research in the last 10 years has shown that, at times, overlapping beliefs may not explain coordination at all. For example, in a large quantitative study of policy elites involved in collaborative regional land use and transportation planning in four regions of California, Henry et al. (2011) found that shared beliefs did not have a statistically significant effect on the occurrence of coordination. Similarly, based on a social network analysis of the Swedish hydraulic fracturing (fracking) subsystem, Nohrstedt and Olofsson (2016) found that, even though large groups of actors shared the belief that fracking infrastructure should not be expanded, only coordination clusters emerged rather than an overall anti-fracking coalition. The group of actors that shared similar beliefs remained "too fragmented to speak of one single dominating anti-fracking coalition" (Nohrstedt and Olofsson, 2016, p. 155).

Second, recent research has shown that, even in cases where overlapping beliefs partly explain coordination, other contextual factors in a given policy subsystem influence coordination too. These factors, which are briefly presented in the following subsections, include the (1) level of contestation in a policy subsystem, (2) access to resources, and (3) trust.

Level of contestation

Recent research on the nuances of the belief homophily concept has found evidence that the level of contestation (also known as the level of conflict or controversy) in a policy subsystem may be a relevant contextual factor that influences the salience of shared beliefs as a predictor of coordination. Policy subsystems are described as being contested "when a population of policy actors diverge strongly in their policy positions, perceive threats from opponents and are unwilling to compromise on policy positions" (Weible et al., 2018, p. 3). Calanni et al. (2015) show that in little contested policy subsystems, beliefs systems are not very likely to predict coordination. They ground their findings on interview and questionnaire data obtained from policy actors in the marine aquaculture industry in the USA. The interviewed actors were organized in marine aquaculture partnerships, which are political bodies “that include governmental and nongovernmental groups that collaborate on policy [. . .] to support the [. . .] regulation of marine aquaculture industry” (Calanni et al., 2015, p. 908). Calanni et al. (2015) show that even though the belief systems of members in these partnerships differ, the jointly acknowledged need for development in these little contested arenas allowed for collaborative interaction beyond the belief similarities.

A study conducted by Weible et al. (2018) looked at a highly contested policy subsystem and the results that complemented the results reported in a paper by (Calanni et al., 2015). Weible et al. (2018) looked at questionnaire data from policy actors involved in fracking in three states in the USA (New York, Colorado, and Texas). Supportive and opposing advocacy coalitions were active in all three states. The political debates that emerged in the states “have been characterized by broad mobilization from diverse policy actors, including landowners and mineral rights owners, local governments, state governments, the oil and gas industry and environmental and citizen-based groups” (Weible et al., 2018, p. 9), which indicates a high level of contestation. Weibel et al.’s study found evidence that policy beliefs can contribute to explaining coordination in such contested policy subsystems.

The above-discussed two studies show that the level of contestation can be an influential mediator. However, the conceptual differentiation between highly and little contested policy subsystems has not yet been sufficiently clarified and empirical evidence for the presented claims is still scarce. It is also slightly surprising that in the highly contested fracking policy system presented by Weible et al. (2018), overlapping beliefs are considered only moderately important.

Access to resources

In addition to the belief homophily argument, some authors have explored whether access to resources influences actors that are interested in coordinating with other policy actors (e.g., Calanni et al., 2015; Elgin, 2015; Henry, 2011; Matti and Sandström, 2011; Weible, 2005). They found evidence that perceived access to resources has some explanatory value for coordination among actors.

Access to resources is a central argument in organizational theory: “organizational survival hinges on the ability to procure critical resources from the external environment” and organizations aim to “reduce uncertainty in the flow of needed resources” by employing a variety of tactics and strategies (Casciaro and Piskorski, 2005, p. 167; Pfeffer, J. and Salancik, G, 1978). In recent ACF literature that deals with access to resources, authors measure this access in a variety of ways. The resources considered include *perceived power* (Matti and Sandström, 2011; Weible, 2005) (Calanni et al., 2015; Henry, 2011; Weible et al., 2018), *financial resources* (Calanni et al., 2015; Weible et al., 2018), *access to expertise* (also called competence) (Calanni et al., 2015; Weible et al., 2018), *formal training* (Elgin, 2015), *capability to use collaborative and analytical tools* (Elgin, 2015), and *organizational capacity* (Elgin, 2015). All but one of the cited studies (Matti and Sandström, 2011) find that access to resources helps to explain coordination among individuals.

However, it should be pointed out that none of the papers focuses solely on access to resources. On the contrary, in all cases access to resources is analyzed together with other factors. For example, Henry (2011) Calanni et al. (2015), and Weible et al. (2018) analyze access to resources in conjunction with the previously discussed belief homophily concept. Although all papers suggest that access to resources may be a reason for actors to coordinate with one another, they all assign it only minor explanatory power.

In general, access to resources seems to be a contributing factor in explanations of coordination. However, as indicated above, its explanatory power is likely to be limited and requires further research.

Trust

Alongside belief homophily and access to resources, trust is a recurring theme in the ACF literature. However, so far, the research conducted on trust within the ACF has been rather unsystematic and the relation between trust and coordination is not very clear.

Some papers in the ACF literature suggest that trust is a dependent variable. For example, Schlager (1995), Sabatier (1998), Weible et al. (2009) and Fischer (2014) suggest that once actors coordinate, trust will emerge. Other authors claim the opposite, that trust influences coordination (Calanni et al., 2015; Fidelman et al., 2014; Henry et al., 2011). We focus on the latter claim, as coordination is the dependent variable in this paper. The findings presented by Fidelman et al. (2014) are straightforward, as they indicate that trust is “critical for establishing and maintaining" coordination (Fidelman et al., 2014, p. 126). Calanni et al. (2015) produce similar evidence and suggest that trust, measured as (perceived) competence and fulfilling promises, predicts coordination. They also qualify the claim that trust is even more important than shared beliefs in little-contested subsystems.

The findings presented by Henry et al. (2011) are slightly more complex than those mentioned above and they are intertwined with beliefs. They found that bonding between actors was not the result of similar or divergent beliefs systems. Instead, they discovered that divergent belief systems lead to an avoidance effect between actors, "rather than [. . .] attraction between agents with similar policy beliefs" (Henry et al., 2011, p. 441). This avoidance effect was then used by brokers trusted by coalition actors. The brokers used actors' transitivity, which is understood as "actors' willingness to trust others that their collaborators trust," to forge coalitions (Henry et al., 2011, p. 423). In other words, Henry et al. (2011) found that actors were not attracted to each other by similar beliefs, but that their belief similarity allowed them to bond when a mutually trusted broker introduced them to each other.

Similar to belief homophily and resource dependence, also trust seems to be an influencing factor for coordination. However, the interplay of trust with the other factors is not yet sufficiently understood and a universally applicable approach to how to measure trust in an ACF framework is still missing.

5.4.1.2 Reasons to defect

Much of the ACF literature on coalitions aims to understand why actors coordinate. However, focusing solely on the reasons that lead to coordination neglects the fact that engaging in coalition building is a process that evolves over time and that members may leave a coalition before the envisioned policy change takes place. The literature review indicates two main reasons for defections from coalitions: the need to satisfy organizational welfare before engaging in political activity, and the need to change allies to increase political influence.

Organizational welfare as a priority

Political actors are often members of political pressure groups that aim to influence government policymaking, legislation, and public opinion. Such pressure groups include, for example, industrial lobby organizations and environmental groups. For the organizations to further their cause, they require resources such as financial or human capital. Elliott and Schlaepfer (2001a, 2001b; Zafonte and Sabatier, 2004) found that major external events can affect the subsystem actors' access to resources (Zafonte and Sabatier, 2004). Examples of such external events include changes in socio-economic conditions, in public opinion, or in systemic governing coalitions and policy decisions, and impacts from other subsystems. Such external perturbations can have positive effects, as well as negative effects. However, negative effects are more often described in the literature. The negative effects include, for example, financial constraints at the organizational level, which then translates to other resource scarcities. In order to maintain their political engagement, members of political pressure groups have an "interest [. . .] in maintaining and increasing their own viability/welfare" (Sabatier, 1998, p. 116). If the required resources are scarce, group actors are torn between the welfare of their organization and the welfare of the coalition in which they are engaged. (Sabatier, 1998) suggests that when organizations face this dilemma, they are likely to prioritize their own organization and defect from the coalition.

Strategic change of allies to increase political influence

Not all members of coalitions are equally engaged in furthering the coalition goals. Weible et al. (2010, p. 524) suggest that coordination and allegiance to a coalition depend on the "centrality of a given issue to the members' belief system and to the members' access to resources." Based on their level of allegiance, coalition members can be classified as principal or peripheral members (peripheral member are sometimes also called auxiliary members) (Weible et al., 2010; Zafonte and Sabatier, 2004).

Larsen et al. (2006) show that core actors are more likely to stay loyal to the coalition, while actors at the periphery may join other coalitions if that helps them increase their political influence. A possible explanation is that the cohesion of core members is stronger due to their shared core policy beliefs, whereas peripheral coalition members are mainly linked by shared secondary beliefs (Nohrstedt, 2010, p. 316).

5.4.1.3 Coordination in nascent policy subsystems

The ACF literature acknowledges that subsystems, and thus the context for coordination, changes over time. Authors differentiate between mature and nascent policy subsystems (Beverwijk et al., 2008; Ingold et al., 2017; Stritch, 2015). In this subsection, we show how the differences between mature and nascent subsystems influence the preconditions for coalition building. The relevant literature is quite limited. Nevertheless, the papers that deal with advocacy coalitions in nascent policy subsystems highlight some substantial differences between mature and nascent subsystems.

In nascent policy subsystems, actors' policy preferences and beliefs are not yet well defined and are somewhat fluid (Ingold et al., 2017). Therefore, it is more difficult for them to identify their ideological peers (Ingold et al., 2017, p. 458), and the belief homophily may not be as salient as in mature policy subsystems. As a result, it is likely that several coalitions will emerge in nascent policy subsystems (Stritch, 2015), and that trust and previous contacts will play a bigger role than belief homophily (Jenkins-Smith et al., 2017).

Given that, by definition, nascent policy subsystems are still emerging, coordination is not yet widespread, and coalitions have not had sufficient time to become established. Consequently, subsystem politics are likely to be influenced by "coalitions of convenience" (Jenkins-Smith et al., 2017) or "advocacy communities" (Stritch, 2015), which are also called ephemeral coalitions (Weible et al., 2019). Furthermore, coordination is likely to be still weak (Beverwijk et al., 2008).

The coalition

Thus far in this paper, our analysis has focused on the individual. Next, we turn to the coalition as the unit of analysis. The first finding is that far fewer of the reviewed papers deal with the coalition as the unit of analysis than with the individual. This means that many conceptual propositions suggested over the years have not yet been underpinned by empirical studies.

Heterogeneity among coalition members

One of the tenets of the advocacy coalition framework is that coalitions are composed of diverse actors from different backgrounds and with different professions (Sabatier, 1998). This assumption is repeatedly supported in empirical studies (e.g., Elgin, 2015, Nohrstedt and Olofsson, 2016, and Cohen et al., 2018). However, this raises the question of whether heterogeneity affects coordination among coalition members. Schlager (1995) suggests that, on the one hand, heterogeneity could present an obstacle to cooperation, since actors are likely to feel they are not treated fairly and thus may be more likely to defect, while on the other hand, heterogeneity is likely to bring to a coalition resources that are more diverse, which may benefit the coalition's political struggle (Schlager, 1995). The analyzed literature shows evidence of the latter (e.g., (Cohen et al., 2018), but the former area of inquiry is seemingly under-researched. This identified gap in the literature is in line with findings reported by Weible et al. (2019, p. 1069), namely that the effects of diversity in coalitions are an area where research is still needed.

Internal processes and organization of advocacy coalitions that influence stability

In addition to claiming that heterogeneity influences coordination within coalitions, Schlager (1995) suggests three approaches that can help to strengthen the coordination within coalitions. The first is that actors in coalitions should adopt a habit of regular interaction. Based on a book by Ostrom (1990), she suggests that repeated interaction "decreases the cost for information exchange and shaping preferences" and it "allows actors to learn that other actors are trustworthy" (Schlager, 1995, p. 250). The second suggested approach is that members of a coalition should be able to sanction other members in order to de-incentivize defection (Schlager, 1995, p. 250). The third approach is to implement processes that ensure actors are treated fairly, not similarly, in order to keep the internal power balance of a coalition intact (Schlager, 1995, 262/263). Schlager specifically refers to imbalances of resources that some members provide in comparison to others. She suggests that it is advisable for the coalition to give such members more say in the goal and strategy setting of the coalition (Schlager, 1995, p. 163). Although there is conceptual support for the first approach suggested by Sabatier (1998), and empirical evidence provided by Lubell (2007) in support of the third approach, there is no other evidence to support or contradict Schlager's three suggestions, thus indicting the need for further research.

5.4.3 The subsystem

Thus far, we have presented our coordination-related findings at the level of the individual and the coalition. In the final subsection of the analysis, we present coordination-related insights at the level of the policy subsystem.

In the ACF, advocacy coalitions are embedded in policy subsystems. However, the configuration of such policy subsystems can vary substantially. The ACF suggests that subsystems can be divided into three categories: unitary subsystems, collaborative subsystems, and adversarial subsystems (Figure 12). How coalitions interact (lack of interaction, collaboration, and competition) determines the type of policy subsystem. We present these three types of subsystems in the following subsections.

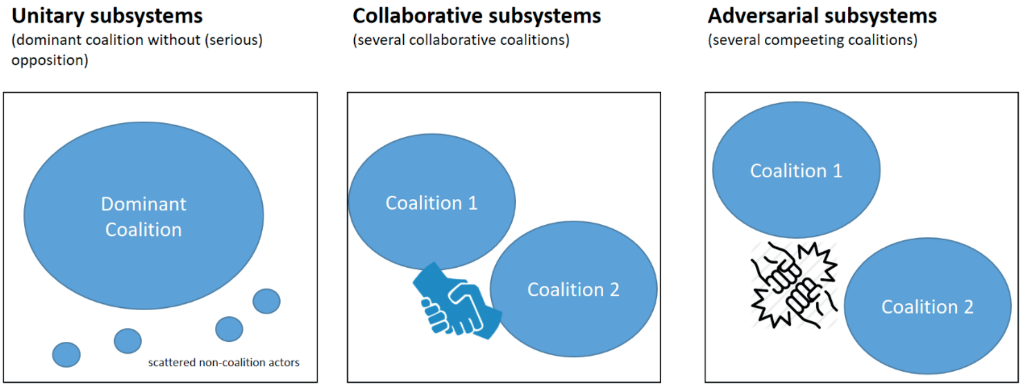

Figure 12: Three different types of policy subsystems.

Unitary subsystems

A unitary political subsystem features a dominant coalition. The coalition includes the majority of political actors and has considerable resources at its disposal to steer the subsystem's course and undermine any opposition. If there is an opposition, it is fragmented and will not have sufficient resources to threaten the influence of the dominant coalition (Weible et al., 2010). A dominant coalition will aim to maintain the status quo by taking incremental political decisions and by dampening any internal or external events that could attract the attention of actors outside the political subsystem (Weible et al., 2010). Furthermore, members of the dominant coalition aim to distribute any benefits among coalition members only (Weible, 2008). Learning among coalition members will be restricted within the dominant coalition, which will largely aim to strengthen existing beliefs (Weible et al., 2010). Coordination will only take place among actors within the dominant coalition (Weible et al., 2010).

The ACF differentiates between major policy change and minor policy change (Sabatier, 1998). Several authors have attempted to describe causalities regarding the emergence of these different types of political change in the three subsystem contexts. In unitary subsystems, due to the concentration of power, the dominant coalition has the capability to lead major policy change. However, if a coalition has already been in a position of power for some time, the urge to facilitate major change will decrease (Fischer, 2014).

Collaborative subsystems

Collaborative subsystems feature several coalitions. The coalitions "continue to disagree but [. . .] are able to find enough common ground to negotiate" (Fidelman et al., 2014; Weible et al., 2010, p. 527). Collaborative coalitions feature high inter- and intra-coalition coordination (Weible, 2008, p. 622). Cooperation between members of different coalitions is often aided by effective policy brokers (also called inter-coalition brokers (Koebele, 2019; Weible et al., 2010). Collaborative subsystems are likely to be less contested than unitary or adversarial subsystems. Hence, belief similarity may not be as predictive for coalition formation as is the case for the other types of subsystems (Koebele, 2019). It is likely that "actors will coordinate for a variety of reasons other than holding shared beliefs, leading to a line-up of allies and opponents that varies over time" (Koebele, 2019, p. 51). Koebele (2019, p. 51) provides evidence that cross-coalition coordination can be both "strategic and short-lived" but also long-term oriented. In collaborative subsystems, authority is decentralized and fragmented across the policy subsystem. Actors in such systems share access to authority and are more likely to allow open participation (Weible, 2008). They aim for win–win solutions (Weible, Siddiki, Pierce, 2011). Furthermore, they prefer policy instruments that are flexible or voluntary in terms of compliance (Koebele, 2019).

Both major and minor policy change is possible in collaborative subsystems. Since regular face-to-face interaction in collaborative subsystems allows actors to learn and build trust, actors from different coalitions can engage in policy learning, which may then facilitate major policy change (Fischer, 2014). However, the collaborative patterns may also lead to "all talk and no action," meaning that "consensus-based procedures may lead to more agreement on the issues but policy participants continue to stick to their value-based policy positions" (Weible et al., 2009).

Adversarial subsystems

Adversarial policy subsystems feature a small number of competitive advocacy coalitions. Members of competitive coalitions have incompatible and polarized beliefs (Weible and Sabatier, 2009), which lead to high levels of conflict and contestation (Weible et al., 2009). The beliefs also lead to coordination that takes place mostly within the coalitions (Weible and Sabatier, 2009). Cross-coalition coordination is scarce. Instead of compromise, coalition members prefer policy designs that lead to clear winners and losers (Weible, 2008). Competing coalitions usually have access to sufficient resources to be able to challenge each other (Weible et al., 2010). In adversarial subsystems, authority can be fragmented, as individual public servants or specific government organizations tend to favor one of the competing coalitions (Weible and Sabatier, 2009). Furthermore, coalition members do not encounter each other face to face on a regular basis, as is the case in collaborative systems. Instead, they are more likely to meet only at court hearings or parliamentary hearings (Weible, Siddiki, Pierce, 2011). These inter-coalition conflicts are compounded as coercive, and prescriptive policies are preferred to win-win solutions (Weible, 2008). A competitive coalition that tries to change the status quo will aim to expand the scope of conflict outside of the policy subsystem by attracting the attention of supportive external actors or other subsystem actors (Weible, 2008). By contrast, a competitive coalition trying to maintain the status quo will aim to keep decisions within a subsystem and limit conflict escalation (Weible, 2008).

In adversarial subsystems, coalitions can interact in two ways. They are either equal or unequal in terms of the power they possess. If they are equal, they are unlikely to implement policy that substantially changes the status quo (Fischer, 2014). If both coalitions are not content with the status quo but neither is able to change policy, they will find themselves in a situation that the ACF describes as a “hurting stalemate” (Ingold, 2011; Weible and Sabatier, 2009). If power is unequally distributed, the coalition that is more powerful will be less susceptible to making concessions to another coalition. As a result, the more powerful coalition might implement path-breaking policy features, which will lead to major policy change (Fischer, 2014).

The three different types of policy subsystem can be seen as stylized archetypes. While these archetypes have been applied and refined (Calanni et al., 2015; Ingold, 2011; Weible, 2008; Weible et al., 2018), one study also shows that subsystems are not necessarily deadlocked in one system type (Weible, Siddiki, Pierce, 2011). In a longitudinal study of water and land policy in the Lake Tahoe Basin, USA, Weible, Siddiki, Pierce (2011) show that the analyzed policy subsystem actually transformed from an adversarial policy subsystem in the 1980s to a collaborative policy subsystem in the 2000s. Thus, their findings suggest that it is quite likely that policy subsystems can also evolve.

5.5 Summary of review

The first aim of this paper has been achieved through the presentation of the findings of the literature review, namely a better understanding of the factors that influence coordination. These findings are briefly summarized as follows.

The review shows that coordination in a policy subsystem can be regarded as occurring at three distinct levels: the individual, the coalition, and the policy subsystem. The level of the individual encompasses the following factors: functional interdependencies, shared beliefs, perceived access to resources, trust, competence, organizational needs, and desire for political influence. The review also shows that research has established differences in actor and coordination structures, which depend on the maturity of the policy subsystem, with more fluid structures in earlier phases. Although many studies of the individual-level perspective have been conducted, there is still a great need for empirical substantiation. For example, even though belief homophily has attracted substantial research, it is still not entirely clear under which external circumstances it functions as a glue for coalitions.

At the level of the coalition, the literature review suggests that heterogeneity among coalition members may influence coordination. However, the relevant body of literature is substantially smaller than that dealing with the individual level and it lacks empirical foundation. Some suggestions have been made for how to increase the cohesion of coalitions, including repeated interaction, mechanisms to sanction members, and mechanisms to ensure that members feel treated fairly. However, the available literature does not go much further than well-argued suggestions.

At the level of the policy subsystem, the literature suggests that the interaction and coordination between coalitions differ, depending on the type(s) of subsystem involved. In this regard, the literature differentiates between unitary, adversarial, and collaborative policy subsystems. In unitary subsystems, coordination only takes place in a single dominant coalition. In adversarial policy subsystems, coordination takes place within two coalitions that compete for dominance. Similar to adversarial policy subsystems, collaborative policy subsystems feature several coalitions. However, the actors are more likely to interact and coordinate with actors from other coalitions. Even though policy subsystems can evolve from one type to another, this is rarely taken into account or discussed in the literature. The development of policy subsystems over periods longer than 10 years seems to offer substantial scope for further research. It would be especially interesting to conduct longitudinal studies, to learn about the factors that influence such developments, and that accelerate the metamorphosis from one type of policy subsystem to another. To do so, certain dilemmas need to be resolved. For example, it is easier to conduct longitudinal studies based primarily on document analyses (Jenkins- Smith et al., 1991; Zafonte and Sabatier, 2004). However, when assessing coordination and its development, documentation - for example of past political debates - can only be categorized as a mediocre data source, as they hardly reflect actual coordination processes as they happen. A more suitable approach might be to conduct several surveys over time (e.g., Weible, Siddiki, Pierce, 2011), but this is a challenging task, requiring long- term financial resources and continuity in the research team.

5.6 Implications for transitions research and limitations

The second aim of this paper is to draw implications from the presented literature review to accelerating sustainability transitions. These implications include specific suggestions for niche actors on how to build powerful coalitions to influence policy process in ways that support the mainstreaming of more sustainable niche configurations.

The results of our analysis of the reviewed papers show that the ACF literature does not deal with accelerating any specific type of development in a policy subsystem. The ACF can be understood as an explanatory framework rather than as a normatively driven framework. Nevertheless, the review identifies a number of factors that influence coalition building. These factors can be divided into two categories: a factor that barely changes over time, and factors that can be influenced by policy actors.

With regard to the factor that can hardly be influenced by democratic policy measures, and, if at all, then only over long periods: the belief system of an actor. Over time, an individual's belief system may change endogenously, but can only be affected exogenously with difficulty, if at all, since it is deeply engrained in that individual. By contrast, coalition building can be supported by establishing intra-coalition brokers who act as bridges between formerly unconnected niche advocates. Such brokers are not only able to bring actors together by pointing out functional overlaps and interdependencies, but can also mediate when there are differences in opinions and divergent policy aspirations. With regard to the second category of factors, actor composition is a factor that coalition members and brokers can influence. In this regard, it seems helpful to ensure that actors with access to a diverse set of resources become members of a coalition. Coalition members and brokers can also influence the layout and structure of their coalition, for example through internal coalition processes that strengthen cohesion and discourage defection. Such processes include the provision of repeated opportunities for interaction and mechanisms that sanction members for non- compliance with the agreed rules.

Based on the three archetypes of policy subsystems, we assume that transition processes evolve from unitary policy subsystems, in which a dominant coalition of policy actors supports an incumbent socio-technical regime. Through coordination, niche actors can form a countercoalition and transform the hitherto unitary subsystem into an adversarial or a collaborative policy subsystem. The type of subsystem created is likely to depend on the willingness of the incumbent actors to collaborate with niche actors. If incumbent actors defend the status quo, their policy subsystem will become an adversarial one. By contrast, if incumbents collaborate, the formerly unitary subsystem will become a collaborative one. This is more likely to come about if the exogenous – or in transition terms, landscape pressure – is high, thus resulting in incumbents having to initiate adaptations in the way they operate in order to remain relevant in a new system.

The advantage of collaborative systems for niche policy actors is that they are more likely to accelerate the diffusion of the innovations they support. This is because collaborative interaction can harness the resources of incumbent actors to accelerate the development of niche innovations. By contrast, the emergence of adversarial policy subsystems may lead to long drawn-out battles between incumbent actors and niche innovation actors. The suggestions for coordination differ, depending on the policy subsystem that develops. In adversarial policy subsystems, niche actors are advised to forge a strong identity and define a clear opponent to combat in order to unify coalition members. Furthermore, it seems advisable for them to accumulate resources for a long struggle. By contrast, in collaborative subsystems, a strong identity and resources are less important, as actors from different coalitions work together and can pool resources. Instead of focusing on accumulating resources, niche policy actors in collaborative subsystems should try to find policy initiatives that unite both incumbent and niche actors.

While niche actors in adversarial policy subsystems are advised to create a strong identity and accumulate resources for a long-lasting struggle, this may not be as important in collaborative subsystems. In collaborative subsystems, the implication is that niche policy actors should put less effort into forging a strong identity and unity among coalition members, and more into identifying policy configurations that both sides can agree on, so that coordination across coalitions will be facilitated and strengthened.

The main limitation of the literature review is that coordination-related literature was only selected based on the mention of the term “advocacy coalition” in the title, abstract or keywords. As became clear during the process of analysis, some peer-reviewed papers that look at coordination in advocacy coalitions and are thus relevant for this review, do not use the term “advocacy coalition” in their title, abstract or keywords. A thorough analysis of the initial corpus identified a number of additional relevant documents based on cross-references, which were then included in the final corpus (Calanni et al., 2015; Ingold and Fischer, 2014; Nohrstedt and Olofsson, 2016; Weible et al., 2018; Wray et al., 2017). However, the limitation remains that the final corpus probably does not include all papers that deal with coordination in advocacy coalitions.

The review highlights the urgent need for empirical findings to underpin the substantial research on what leads to coordination at the level of individuals. For example, although belief homophily has been the subject of extensive research, it is still not entirely clear under what external circumstances it functions as the glue for coalitions. At the level of the coalition, the influence of diversity on the coalition-building process is yet not well understood. While there are some suggestions that actor diversity can help to activate different political resources, a more diverse actor set can also inhibit coordination efficiency. Other suggestions have been made for how to manage coalitions, but they lack an empirical foundation. At the level of the policy subsystem, research on how coalitions interact with each other is scarce. In this respect, it would be of interest to understand better how the type of policy subsystem influences the development of advocacy coalitions and under which circumstances subsystems evolve from one type (unitary, collaborative, and adversarial) to another. A better understanding of these factors and circumstances would also help cross-pollination between studies relating to the advocacy coalition framework and sustainability transitions research.

6 | Conclusion

This thesis started out from the observation that in comparison to the electricity system in Germany, which has seen a rapid transition in recent decades, the heating system in the country has progressed at a much slower and with lower dynamics. This led to the development of the concept of configurational TIS in the thesis, in contrast to generic TIS. After conceptualizing (Chapter 2) and empirically studying this novel concept (Chapter 3), the focus was directed towards the actor structures in configurational TIS (Chapter 4). The related findings motivated a review of the state of knowledge about coalition building (Chapter 5). In this final chapter (Chapter 6), the main conclusions of this thesis are presented, based on the conducted research and taking up the research questions from Chapter 1. First, conclusions are drawn concerning the typical problems that hinder the development of configurational TIS (Chapter 6.1), followed by conclusions on how coordination typically plays out in configurational TIS (Chapter 6.2). Based on these conclusions, recommendations are developed for how to intervene and thereby render the development of configurational TIS dynamic (Chapter 6.3). Thereafter, the overall implications for transitions research are presented, the limitations discussed and avenues for further research outlined (Chapter 6.4).

6.1 Dynamics of change in configurational innovation systems

The original aim of the research for this thesis was to develop a better understanding of the underlying reasons why innovation systems exhibit substantially different dynamics of change in an ongoing transition. This led to a study of the role of local context dependence and how local contingencies influence the diffusion dynamics of sustainable innovations. The motivation to study the influence of local context dependencies was grounded in the observation of differing development dynamics in the German heating system and electricity system. While the share of renewable energy in the electricity system has increased substantially over the last two decades, the share of renewable energy in the heating system has only experienced incremental growth. This is a problematic theoretical issue, since both systems need to decarbonize swiftly so that Germany can fulfill its greenhouse gas emission reduction targets.

In this thesis the notion of configurational TIS has been developed and used to explain the difference in system development dynamics, in Chapter 2 and Chapter 3. Configurational innovations systems, such as the German heating system, evolve around innovations that are more dependent on the local context than this is the case for generic innovations. The results presented in Chapter 2 and Chapter 3 suggest that this more pronounced local context dependency implies functional development patterns that hinder a rapid transition of configurational TIS. This subchapters summarizes the main differences between configurational TIS and generic TIS in terms of structures and functions based on the empirical analysis of the German heating system.

With regard to *actors*, Chapter 2 and Chapter 3 provide evidence, for both the heating system in Germany as a whole and for the case study of district heating, that actor structures in configurational TIS are more heterogeneous and fragmented than is the case in generic TIS. This finding is supported by evidence presented in Chapter 4, in which a dispersed actor structure is shown for the German heating system.

Such a more fragmented actor structure goes hand in hand with dispersed *interactions*, which are characterized by more fragmented sets of smaller coalitions that emerged over time in the heat system (Chapter 4). As shown in Chapter 4, this is problematic for transitions because small and independent coalitions focus rather on their own goals and visions instead of working together for the greater cause. In the analyzed case, the German heating system (Chapter 4), this opaque coordination pattern has not allowed for a grand coalition with a single encompassing vision to emerge. A lack of such a coalition is detrimental to the unfolding of a transition, since an encompassing coalition is more likely to be sufficiently powerful to mobilize financial and political resources in order to change the selection environment (cf. Chapter 5), so that the diffusion of configurational innovations would be advanced. Consequently, the lack of such a coalition is likely to continue to hamper the dynamics of the overall transition.

Similar to the higher degree of fragmentation of actors and coalitions, the analysis in Chapter 2 and Chapter 3 shows that the structure of hard (formalized) *institutions* is also likely to be more fragmented. In the presented heating case (Chapter 2 and Chapter 3), the financial support instruments were dispersed, smaller-scale, partly inconsistent, and generally accumulated less financial weight compared with the financial support in the electricity system. This is likely to have had repercussions at the local level, where different types of stakeholder groups have had to put substantial efforts into finding the right funding programs for their projects. In the analyzed case, this also had implications for the performance of TIS functions (as elaborated on below).

Finally, since local contingencies are very diverse in configurational TIS, the analyzed case shows that they are likely to be influenced in their diffusion by a greater variety of *infrastructure* (cf. Chapter 2 and Chapter 3). There are three forms of infrastructure: *physical infrastructure*, *financial infrastructure*, and *knowledge infrastructure*. Due to the higher local context dependence, configurational innovations are more exposed to the influence of physical infrastructure than this is the case for generic innovations. Regardless of whether a technology is to replace an old technology or whether it is to be implemented on a greenfield site, the presented data suggest that implementation of configurational innovations is likely to be more exposed to more (incumbent) physical infrastructure than this is the case for generic innovations. In the case of heat technologies, physical infrastructure can be in the form of, for example, the age of a building, level of insulation, type of radiators previously used, availability of district heating, and the possibility of using geothermal energy. In contrast to physical infrastructure, financial infrastructure tends to be more fragmented in configurational TIS than is the case in generic TIS. This may partly be traced back to fragmented hard institutions, which facilitate the influx of financial resources, as well as to the greater variety of solutions that require tailor-made financial schemes. In addition to infrastructure and financial infrastructure, knowledge infrastructure is key for the development of technological innovation systems. Due to unique application designs on the basis of ever-changing local contingencies, each installer or project developer in the analyzed heating system case needed to be equipped with maximum component expertise and knowledge of how to interlink them (Chapter 2 and Chapter 3). Hence, the need for local knowledge infrastructure is likely to be substantially greater in configurational TIS than is the case in generic TIS.

The above-described structural differences between configurational and generic innovation systems have several implications for the dynamics in system change. *First*, in contrast to generic TIS, in configurational TIS dominant designs are likely to develop slowly, if at all (Chapter 2 and Chapter 3). Dominant designs may develop at the component level, but they are less likely to emerge at the implementation level, due to the ever-changing contingencies. By contrast, in generic TIS, dominant designs can emerge in shorter periods (see Chapter 2). Experimentation is still needed, but entrepreneurs can focus their skills and resources much earlier on refining a limited number of solutions. In turn, in configurational TIS continuous experimentation persists, which is problematic because it leads to low levels of learning by replication and hence to limited economies of scale that can be taken advantage of.

A *second* structural difference between configurational and generic innovation systems is that in configurational TIS the lack of standardization during the implementation process requires entrepreneurs to focus on designing tailor-made solutions. In order to implement tailor-made solutions, substantially more knowledge development is required. At the system level, this is likely to slow down cost reduction since the installation of configurational technologies takes substantially more time than the installation of generic technology and thus standardized technology.

As a *third* structural difference between configurational and generic innovation systems, due to the fragmented structure of configurational TIS, knowledge diffusion is likely to be hampered. Because of higher fragmentation of knowledge development in configurational TIS (compared with in generic TIS), knowledge diffusion in configurational TIS needs to happen among a broader group of people, as demonstrated in the German heating system (Chapter 2 and Chapter 3). This is problematic for two reasons. First, there is a special need for horizontal knowledge exchange across geographies in configurational TIS, which tends to be lacking. Installers need to have knowledge of all solutions and combinations available so they can decide locally which configuration is the right one to install. If specific knowledge about new solutions is not available, local installers are likely to fall back on traditional solutions, for which they have built a good foundation of knowledge. Second, configurational TIS are likely to face a special need for vertical knowledge exchange. Since new technologies and configurations are often financially supported by the government, a vertical knowledge exchange between policymakers and local actors concerning these supportive schemes is crucial, so that local decision-makers are able to assess the financial viability of innovative solutions. Furthermore, due to ever-changing local contingencies, technology companies that develop new solutions and components have a strong need to learn about local needs. If the exchange of knowledge is insufficient, technology companies are unlikely to develop fitting components and solutions for the large variety of applications.

A *fourth* structural difference between configurational and generic innovation systems, and one that also explains the slower development of configurational TIS, is the lack of guidance of search, which configurational innovations systems are more likely to experience than generic innovations systems. Due to the broader variety of technologies and the actors associated with them, finding a common understanding of how a transition could appear is harder in configurational settings (Chapter 2 and Chapter 4). However, lack of a common vision goes hand in hand with a lack of coordination and political power of actors that support innovative, more sustainable solutions (Chapter 4). This is problematic, as lack of coordination that leads to unclear guidance of search leads to a lack of government resources funneled into research and development, and into support schemes that incentivize the diffusion of configurational innovations. Furthermore, in Chapter 3 it is shown that policies at the national level, which do not take into account the local context, are likely to be insufficient to overcome the multitude of barriers imposed by local contingencies of configurational TIS.

A *fifth* structural difference between configurational and generic innovation systems concerns problematic market formation. As shown in Chapter 2 and Chapter 3, configurational TIS are likely to face hampered market creation due to the fragmented and insufficient support schemes (hard institutions), as well as limited guidance of search and lack of sufficient knowledge diffusion. In contrast, in generic TIS, clearer technological identities, as well as less fragmentation among actors, lead to advantages in market formation, as can be seen in the German electricity system (Chapter 2). Inhibited market formation is problematic because it leads to limited demand, which in turn reduces the inflow of financial resources for entrepreneurs and hence inhibits their opportunity for continued experimentation and growth.

A *sixth* structural difference between configurational and generic innovation systems, and one that is problematic in configurational TIS, is an inhibited mobilization of resources. Without the mobilization of sufficient resources, the basic inputs for other TIS functions are limited. Due to lacking unclear guidance of search (Chapter 2) and lack of clear market formation (Chapter 2) in configurational TIS, funders such as private investors or state agencies face more complexity in deciding where to allocate financial and other types of resources. This leads to considerably less available financial capital that could be funneled into configurational TIS (see Chapter 2). Furthermore, since configurational innovations are likely to be diverse, government support schemes are likely to be more diverse and fragmented, which means that local installers are likely to have less clear business cases and face greater challenges in finding not only technologically fitting but also financially attractive solutions. For example, in the electricity system, only wind power and solar PV were quickly shortlisted as eligible for substantial government support. In order to promote specifically the diffusion of the two technologies, the Renewable Energy Sources Act entered into force in 2021. The focus on a low number of technologies allowed for the government support scheme to provide a clear, concise and financially attractive funding framework, which could be easily understood by local installers. By contrast, the support schemes for heat-related technologies in Germany are less concise and hence less easy to understand, which as a result has meant that fewer actors have made efforts to seek funding.

A *seventh* structural difference between configurational TIS and generic TIS is the build- up of legitimacy for the innovations in terms of their scope. The build-up of legitimacy is difficult in configurational TIS because bodies that can work to stimulate the creation of legitimacy on the national level, such as industrial actors or political power pressure groups, tend to be rather decentralized and less aligned with regards to their expectations and interests (as shown in Chapter 4). By contrast, in generic TIS coordination is likely to be easier due to less fragmented actor structures and hence the formation of groups with political power is also easier, which in turn fosters the process of legitimation (as shown for the German electricity system, see Chapter 2). This more decentralized structure is problematic because it hampers meaningful interaction and coordination, which is necessary for settling internal quarrels and for engaging in joint action for legitimacy. Furthermore, due to the higher level of local context dependence, legitimacy on the point of implementation plays a substantially larger role in configurational TIS than is the case in generic TIS. While in a generic TIS, households or decision-makers can make decisions rather easily, in configurational TIS it is more often the case that a larger group of people are part of the decision-making process, as shown in Chapter 3. In such situations, legitimacy is crucial and sometimes not simple to obtain.

In an ideal setting, well-performing TIS functions fuel each other, leading to cumulative causation (Suurs et al., 2010). However, due to the substantial number of structural impediments that the development of configurational TIS is exposed to, cumulative causation is less probable, and more specific efforts are necessary to enhance the development.

6.2 Coordination in configurational innovation systems

While the first part of the thesis focuses on the systemic properties of configurational TIS, the second part of the thesis (Chapter 4 and Chapter 5) focuses on how actors can coordinate their strategies in order to alter the institutional selection environment to which sustainable niche solutions are exposed. Chapter 4 shows, through an empirical mixed-method case study, how interest groups in the German domestic heating system coordinate their lobby activities in order to shape their institutional environment. Chapter 5 presents a literature review of the Advocacy Coalition Framework and provides insights into the factors that influence coordination among policy actors, as well as how actors can succeed in building strong coalitions.

The analysis in Chapter 4 suggests that due to a wider variety of technologies and components in configurational TIS compared with generic TIS, also the number of actors involved in configurational TIS are likely to be higher and their structure more fragmented, which has implications for coordination. While cohesion in smaller groups is probably easier to organize, with fragmented actor sets in configurational TIS comes a greater variety of visions for the future and differing interests related to the preferred institutional conditions. The analysis presented in Chapter 4 indicates that while interest groups in configurational innovation systems are capable of cooperating and building coalitions, the great variety of visions and affiliated interests pose substantial challenges to meaningful interaction and coordinated agency. The main reason is that a variety of actors also comes with a variety of visions of the future, and that uniting actors that have different visions of the future under a common vision is challenging. Furthermore, as presented in the case study, the emergence of powerful coalitions was hindered due to the fact that a number of low-carbon niche interest groups deliberately cooperated with incumbent technology interest groups even though they envisioned very different end- states of the transition (e.g., low-carbon versus fossil fuel based). Based on these hampering factors, it can be concluded that large and cohesive pro-transition coalitions are more difficult to organize in a configurational TIS compared with in generic innovation systems.

The ACF review presented in Chapter 5 suggests that coordination between policy- related actors is influenced by a variety of factors. While the initial proposal of the ACF was that coordination among policy-related actors is mainly attributable to overlapping belief systems (Sabatier, 1988), the presented review suggests that a variety of factors influence coordination. In addition to similar beliefs, also trust plays a major role, as well as outcome-oriented motivations at the individual level, such as the urge for political power, access to resources, and access to the expertise of other actors. Apart from these factors, the review also shows that a fundamental prerequisite for coordination is that actors need to have the opportunity to meet and engage with each other so that potential coalition members can learn about their respective beliefs, competences, and resources, and to build trust among them. In order to provide such opportunities to meet and engage, the ACF promotes the role of coalition brokers.

The new insights from the literature review have implications for the development of configurational TIS and transitions in general. While the actor structure in generic TIS is likely to be rather compact, it is quite probable that actors meet each other on a regular basis, such as at industry meetings and trade fairs or through political dialogues. Hence, in these systems, brokers are able to help coalitions to emerge and to institutionalize. However, their role in configurational TIS is likely to be more important due to the higher fragmentation in such innovation systems. Due to actor fragmentation in configurational TIS, action spheres of relevant actors overlap less and venues where actors can meet across geographies and administrative levels are likely to be scarcer than in generic TIS. Therefore, to enable interaction the role of brokers is probably more important in configurational TIS than in generic TIS. Thus, as a key conclusion, the need for well- connected brokers that organize and provide venues for exchange and networking is likely to be substantially higher for the development of configurational TIS than is the case for the development of generic TIS.

Concerning the composition of coalitions, the review in Chapter 5 shows that the ACF literature has not yet provided conclusive answers as to how the heterogeneity of actors (e.g., regarding their role as policymakers, industry representatives, and journalists) may exert impact on the coordination within a coalition. Whether actors' heterogeneity has overall positive or adversarial effects on coalition building is yet to be determined in the ACF literature. Taking into account the findings presented in Chapter 4, it appears more likely that heterogeneity will hamper coalition building than facilitate it. However, if actors overcome collective action problems they may be able to build powerful coalitions, since they may be given the opportunity to harness a variety of financial and non-financial resources that other actors bring to the coalition.

6.3 How to intervene in configurational innovation systems

The thesis shows that configurational TIS features a number of structural characteristics that are likely to impede transition processes. In order to stimulate the development of configurational TIS, three key recommendations for policymakers and practitioners are be identified in this subchapter.

A key insight from this thesis is that the evolution of configurational TIS is substantially influenced by the level of context dependence that impacts their transition. The higher the diversity of local contingencies, the more technologies and components are needed to offer adequately customizable solutions. With an increased number of solutions, the number of combinations increases exponentially, which leads to ever more complex systems. With higher complexity, systems become more difficult to govern. Therefore, in order to facilitate governance, policymakers should aim to reduce the number of configurations and thereby decrease complexity. To do so, policymakers could aim to identify the most promising solutions, for example based on their technology readiness or sustainability potential, and direct policy measures towards those solutions. Furthermore, complexity could be reduced by proactively implementing policies that decrease the attractiveness of other solutions. To accelerate sustainability transitions specifically, it may be advisable to remove unsustainable options first. However, this should only be done under the condition that sustainable alternatives are readily available.

Another promising strategy is to support the facilitation of horizontal and vertical knowledge exchange. Horizontal knowledge exchange is crucial in local context dependent configurational TIS, as due to the diversity of applications, as well as combinable components, individuals may lose their overview and hence may not implement optimal solutions. Consequently, facilitating horizontal knowledge exchange at the regional level may give the implementing actors the opportunity to learn about solutions from each other and thus improve their implementation skills. In contrast to horizontal knowledge exchange, vertical knowledge exchange refers to information flows across administrative levels, such as between the national and local level. This exchange is specifically needed in configurational systems, since 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.

The results show that large coalitions are less likely to emerge in configurational settings. Coordination of such coalitions is especially challenging in configurational TIS, as in such systems fragmented and dispersed actor structures make interaction across geographical and administrative levels difficult. This is further complicated by the large number of visions and special interests likely to be encountered in configurational TIS. However, based on the research presented in this thesis it is advisable for actors to focus on building such large coalitions, since that is a main approach to modify the institutional selection environment in a way that allows the diffusion of desired technologies and solutions to flourish. To build meaningful and powerful coalitions, there is a need for reflexivity with regard to the importance of coalition building in which the type of system actors operate. Hopefully, this thesis will help to stimulate such reflexivity and help actors to build and forge strong coalitions that advocate institutional change that facilitates sustainable development.

6.4 Critical appraisal and further research

Whereas in the preceding subchapters the focus is on the empirical and theoretical contributions of this thesis, in this subchapter the focus is on a critical reflection of the results and the limitations of the analyses' validity. Furthermore, interesting avenues for further research are highlighted.

The main contribution of this thesis is that it proposes and develops the concept of configurational TIS for highly fragmented innovation systems and how this impacts the transitions of such TIS. The starting point for these conceptual developments is the observation that the German heating and the electricity sector have developed quite differently. The slow transition of the heating sector also served as the guiding empirical case for several of the papers that are part of this thesis. This enabled an empirical link across the different studies and the underpinning of the theoretical concepts with data- driven research. However, the focus on the heating sector, and on top of this the focus of the German heat sector, also constitutes the major limitation of this thesis. This affects the generalization of the findings to other TIS. Thus, further research is needed to validate the concept for other TIS and other contexts.

Additionally, since the three empirical studies only allowed for a snapshot analysis, it would be interesting in future studies to explore coordination and its dynamics over time. For example, a replication of the study presented in Chapter 4 might provide valuable insights into how coordination of actors in configurational TIS develops over time.

Additionally, while the presented coordination study suggests reasons for what inhibits coordination in configurational TIS, the presented literature review suggests starting points for how to structure and shape coalitions that may accumulate influence over time. To enrich the theoretical starting points with empirical evidence, future studies could gather evidence about what drives coordination and coalition building. Lastly, as shown in Chapter 5, some authors of AFC-related literature suggest that coordination among actors in policy subsystems may change over time. For example, (Weible, Siddiki, Pierce, 2011) observed that interaction in a political subsystem evolved over several decades from an adversarial subsystem to a collaborative subsystem. Hence, it is possible that interaction and coordination might evolve also during transition processes and thus have different characteristics at various stages. Therefore, empirically substantiating whether coordination and interaction changes over time in parallel to system change could be another interesting avenue for research.

By introducing the notion of configurational TIS and analyzing coordination in a configurational system, this thesis contributes to the theoretical advancement of the sustainability transitions research field. It is critical to have a better understanding of the specific dynamics in different types of technological innovation systems in order to formulate appropriate policies and strategies that could help to build better and more sustainable societies.

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Appendix A, B, C

APPENDIX A

Table 13: Interviews conducted for study one presented in chapter two

Number	Position	Affiliation	Date	Number	Position	Affiliation	Date
1	Mayor	Project #1	June 2016	20	Mayor and co- initiator	Project #4	June 2016
2	CEO of project developer	Project #1	June 2016	21	CEO of local agri-enterprise and co-initiator	Project #4	June 2016
3	Project manager of project developer	Project #1	June 2016	22	Member of executive board of local energy cooperative and co-initiator	Project #4	June 2016
4	Leader of local environmental group	Project #1	June 2016	23	Mayor	Project #5	July 2016
5	CEO of local waste heat supply company	Project #1	June 2016	24	CEO of local heat technology enterprise and co- initiator	Project #5	July 2016
6	Former head of local energy agency	Project #1	June 2016	25	CEO of local software enterprise and co-initiator	Project #5	July 2016
7	CEO of local heating oil supply company	Project #1	June 2016	26	Former CEO of local utility company and initiator	Project #6	August 2016
8	Local civil servant and co-initiator	Project #2	June 2016	27	Civil servant in state treasury ministry and project manager	Project #6	August 2016

Number	Position	Affiliation	Date	Number	Position	Affiliation	Date
9	CEO of local renewable energy company and co-initiator	Project #2	June 2016	28	Civil servant in regional construction authority and project manager	Project #6	September 2016
10	Mayor	Project #2	June 2016	29	Energy researcher	Expert	May 2016
11	Former mayor	Project #2	June 2016	30	Representative of heat tech association	Expert	July 2016
12	CEO of tech provider and project developer	Project #2	June 2016	31	Representative of renewable energy association	Expert	July 2016
13	Researcher at local technical college	Project #2	July 2016	32	Representative of heat technology think tank	Expert	August 2016
14	Manager in national utility company	Project #2	July 2016	33	Representative of fossil heat tech campaigning group	Expert	August 2016
15	Initiator and member of local parliament	Project #3	July 2016	34	Representative of national chimney sweeps association	Expert	August 2016
16	City counsellor	Project #3	July 2016	35	Manager at integrated heat technology incumbent	Expert	August 2016
17	City project manager	Project #3	July 2016	36	Heat-related project manager of state-level energy agency	Expert	November 2016

Number	Position	Affiliation	Date	Number	Position	Affiliation	Date
18	CTO of local utility company	Project #3	July 2016	37	Manager at a pipe tech company	Expert	November 2016
19	Vice president of local utility company	Project #3	July 2016				

APPENDIX B

Table 14: List of documents in the final corpus

Names	**Year**	Type	**Geographical level**	**Geographical area**	**Policy issue**
Sabatier	1988	Conceptual article	–	–	–
Jenkins-Smith et al.	1991	Empirical article	national	USA	Energy policy
Sabatier & Jenkins Smith	1993	Book	–	–	–
Schlager	1995	Conceptual article	–	–	–
Sabatier	1998	Conceptual article	–	–	–
Zafonte & Sabatier	1998	Empirical article	regional	USA	Marine / water policy
Fenger & Klok	2001	Empirical article	national	USA	Energy policy
Kübler	2001	Empirical article	national	Switzerland	Pharmacy / drug policy
Elliott & Schlaepfer	2001	Empirical article	National	Sweden	Forest policy
Elliott & Schlaepfer	2001	Empirical article	National	Sweden	Forest policy
Zafonte & Sabatier	2004	Empirical article	National	USA	Automotive pollution control policy
Weible	2005	Empirical article	State	USA	Maritime/water policy
Weible & Sabatier	2005	Empirical article	State	USA	Maritime/water policy
Larsen et al.	2006	Empirical article	National	Denmark	Pharmacy/drug policy
Lubell	2007	Empirical article	Regional	USA	Water supply policy
Bverwijk et al.	2008	Empirical article	National	Mozambique	Higher education policy
Weible	2008	Conceptual article	–	–	–
Weible & Sabatier	2009	Empirical article	Regional	USA	Maritime/water policy
Weible et al.	2009	Review article	–	–	–
Norstedt	2010	Empirical article	National	Sweden	Energy policy
Weible et al.	2010	Empirical article	State	USA	Marine/water policy
Weible et al.	2011	Empirical article	Regional	USA	Maritime/water policy
Henry	2011	Empirical article	Regional	USA	Regional planning policy

Names	**Year**	Type	**Geographical level**	**Geographical area**	**Policy issue**
Ingold	2011	Empirical article	National	Switzerland	Climate policy
Henry et al.	2011	Empirical article	Regional	USA	Land-use and transportation planning policy
Matti & Sandström	2011	Empirical article	Regional	Sweden	Carnivore management policy
Matti & Sandström	2013	Empirical article	Regional	Sweden	Carnivore management policy
Fidelman et al.	2014	Empirical article	Supranational	Southeast Asia-Pacific coral triangle	Maritime/water policy
Fischer	2014	Empirical article	National	Switzerland	Numerous
Ingold & Fischer	2014	Empirical article	National	Switzerland	Climate policy
Jenkins-Smith et al.	2014	Conceptual book chapter	–	–	–
Calanni et al.	2015	Empirical article	Regional	USA	Maritime/water policy
Elgin	2015	Empirical article	State	National	Climate policy
Stritch	2015	Empirical article	National	Canada	Trade union policy
Norstedt & Olofsson	2016	Review article	–	–	–
Norstedt & Olofsson	2016	Book chapter	National	Sweden	Fracking policy
Ingold et al.	2017	Empirical article	National	UK, Switzerland	Fracking policy
Pierce et al.	2017	Review article	–	–	–
Wray et al.	2017	Empirical article	Supranational	Global	Tobacco control policy
Cohen et al.	2018	Empirical article	Regional	USA	Workplace safety policy
Weible et al.	2018	Empirical article	Regional	USA	Fracking policy
Weible et al.	2019	Conceptual article	–	–	–
Koebele	2019	Empirical article	Regional	USA	Water supply policy

APPENDIX C

Code tree used for literature review in Chapter 5

Factors influencing the following internal coalition processes:

- Coordination
- Stability
- Defection
- Cooperation (synonym for coordination in the ACF literature)
- Collaboration (synonym for coordination in the ACF literature)

Paper characteristics:

- Type of paper
  - empirical or conceptual
    - if empirical: qualitative or quantitative data
- Country

Policy subsystem

Summary

Wetenschappelijke samenvatting

De Duitse *Energiewende* wordt alom gezien als een succesvolle transitie, waarbij een energiesysteem tamelijk snel van fossiele brandstoffen overstapt op andere, niet-fossiele, energiebronnen. Duitsland faseert kernenergie uit, richt zich op het opwekken van hernieuwbare energie en heeft een strategie geïmplementeerd om afscheid te nemen van kolen als energiebron. Als we echter de term ‘energie’ en de bijbehorende processen in Duitsland onder de loep nemen, dan is het duidelijk dat de energietransitie met name binnen de elektriciteitssector heeft plaatsvindt; veel minder is in andere sectoren bereikt, zoals in het warmtesysteem. Dit lijkt verrassend gezien de overeenkomsten tussen het warmte- en het elektriciteitssysteem: beide systemen zijn ingebed in grotendeels dezelfde nationale, geografische, politieke, maatschappelijke en institutionele omgeving. Het waargenomen verschil in ontwikkeling vormt de basis voor deze thesis waarbij de volgende onderzoeksvraag centraal staat: waarom verschillen transities in vergelijkbare sectoren qua snelheid?

Om deze discrepantie nader te onderzoeken, gaat de thesis verder in op concepten uit het veld van duurzaamheidstransities, die een onderzoeksstroming op zich in de literatuur is gaan vormen. Het eerste gedeelte van de thesis analyseert de structurele eigenschappen van het Duitse warmtesysteem, het tweede gedeelte van de thesis probeert een beter begrip van de actoren en hun invloed te krijgen.

Deze thesis hanteert de Technological Innovation System (TIS) benadering om de structurele eigenschappen van het Duitse warmte- en elektriciteitssysteem te analyseren. Met de TIS-benadering kan een diepgaande systeemanalyse worden uitgevoerd van de opkomst- en verspreidingsdynamiek van technologische innovaties. Op basis van dergelijke analyses kunnen inzichten worden afgeleid welke factoren verhinderen dat dergelijke innovaties zich verspreiden en welke maatregelen genomen kunnen worden om de verspreiding van innovaties wel verder te stimuleren qua bereik. Een essentiële voorwaarde voor het slagen van een energietransitie is dat innovaties die goederen en diensten op een duurzamere manier kunnen leveren, breed worden verspreid. Vanuit dat oogpunt is het logisch om de TIS-benadering te gebruiken om de onderzoeksvraag te beantwoorden, aangezien de TIS zich focust op verspreiding.

De Duitse warmtetransitie kan niet goed begrepen worden zonder aanpassingen aan de TIS-benadering. Een belangrijk inzicht is dat de Duitse warmtetransitie sterk beïnvloed wordt door de lokale context - waar verandering nog plaats moet vinden. Aangezien warmte niet op een goedkope manier kan worden getransporteerd, zijn vraag en aanbod van warmte in hoge mate geografisch met elkaar verbonden. Warmtegeneratoren moeten daardoor ook lokaal worden geïnstalleerd. Door deze noodzaak van lokale implementatie beïnvloedt de lokale context in substantiële mate de selectie en implementatie van het soort warmtegenerator. Aangezien ieder gebouw uniek is, moet elk nieuw geïnstalleerd warmtesysteem worden geconfigureerd aan de lokale omstandigheden.
Daartegenover staat elektriciteit, dat over lange afstanden kan worden getransporteerd via elektriciteitskabels tegen lage kosten en waarin vraag en aanbod geografisch losgekoppeld zijn, waardoor de implementatie daar kan plaatsvinden waar het het makkelijkst is. De implementatie van elektriciteitstechnologieën zoals windturbines en zonnepanelen bijvoorbeeld vereisen minder specifieke aanpassingen aan de lokale context en kunnen daardoor op grote schaal worden geproduceerd en toegepast in zo ongeveer iedere algemene setting.

Op basis van deze bevindingen kunnen warmtetechnologieën worden getypeerd als configurationele technologieën en elektriciteitstechnologieën als generieke technologieën. Gebruikmakend van dit onderscheid introduceert deze thesis het begrip configurationele innovatiesystemen (configurationele TIS) voor technologieën die rond configurationele technologieën opkomen en generieke innovatiesystemen (generieke TIS) voor technologieën die generiek optreden. Dit is een aanvulling op de bestaande onderzoeksliteratuur over TIS doordat het aantoont dat configurationele TIS-systemen zich op een langzamer tempo ontwikkelen dan generieke TIS-systemen.

Terwijl dit onderscheid tussen generieke en configurationele technologieën een beperkte omvang heeft, heeft het wel negatieve gevolgen voor het definiëren van belangrijke concepten en essentiële processen van technologische innovatiesystemen: doordat ze in hoge mate afhankelijk zijn van de lokale context, brengt configurationele TIS een gefragmenteerdere structuur van actoren, interacties en instituties met zich mee. Uit het empirische bewijs van deze thesis komt naar voren dat door deze gefragmenteerde structuur configurationele TIS-systemen waarschijnlijk problematische ontwikkelingspatronen vertonen, die zowel een snelle verspreiding van duurzamere innovaties verhinderen als ook (energie-)transities in zijn geheel. Een voorbeeld:

doordat nieuwe verwarmingssystemen meer rekening moeten houden met lokale onzekerheden, kunnen ze niet net zoals elektriciteitstechnologieën worden gestandaardiseerd, waardoor er minder ruimte is voor het opkomen van dominante designs die op grote schaal kunnen worden geproduceerd en geïmplementeerd door een relatief kleine groep actoren. Verder bestaan er, door de verschillende lokale contexten, verschillende soorten verwarmingssystemen, die afzonderlijk van elkaar gesteund worden door een niet onaanzienlijk aantal actorgroeperingen. Het verenigen van deze tamelijk diverse groep actoren om de legitimiteit en urgentie van de transitie te faciliteren en om te lobbyen voor een duidelijk en financieel ondersteunend beleidskader is moeilijker dan het verenigen van de relatief compacte groep spelers op het gebied van generieke elektriciteitssystemen (TIS).

Het verschil tussen configurationele en generieke TIS-systemen is in twee onderzoeken uiteengezet. De eerste studie vergelijkt de ontwikkeling van de overwegend configurationele Duitse verwarmings-TIS met de overwegend generieke Duitse elektriciteits-TIS en zet het concept van configurationele TIS uiteen. De tweede studie zoomt in op stadsverwarming, een specifiek type configurationele technologie.

De ontwikkeling van TIS-systemen wordt niet alleen beïnvloed door zijn systemische karakter, maar ook door de manier waarop tussenpersonen dan wel organisaties gebruik maken van hun invloed en macht. De verwachting is dat ook verschillen in het systeem tussen generieke en configurationele TIS van invloed zijn op de context waarin actoren in dit systeem opereren. Oftewel, vanuit een wetenschappelijk oogpunt is het interessant om meer inzicht te krijgen in hoe actoren daadwerkelijk opereren in configurationele omgevingen. Terwijl in het eerste gedeelte van de thesis de focus ligt op het introduceren en aanvullen van het concept ‘configurationeel innovatiesysteem’, ligt de focus van het tweede gedeelte op de actoren en op de mogelijke invloed die ze uitoefenen binnen configurationele TIS-systemen.

In een derde empirische studie is daarom het coördinatiegedrag van industriële groeperingen voor een bepaald type verwarmingssysteem geanalyseerd. De resultaten geven aan dat de gefragmenteerde structuur van configurationele systemen niet alleen van invloed is op systemische ontwikkelingspatronen, maar ook op hun invloed en samenwerking. Doordat de actorenstructuur gefragmenteerder is binnen configurationele systemen is het aannemelijk dat dit gepaard gaat met uiteenlopende belangen en visies. De grote verscheidenheid aan belangen en visies is in principe niet schadelijk voor de ontwikkeling van TIS, maar is problematisch doordat het coördineren van deze verschillende actoren blijkbaar lastiger is. Dit heeft als resultaat, door deze verschillende belangen en visies, dat er een relatief grote groep van kleine samenwerkingsverbanden bestaat binnen configurationele TIS. Het is nogal een uitdaging om deze samen te brengen in een sterk(er) samenwerkingsverband dat duurzame verandering promoot.

Het doel van deze thesis is om, nadat het heeft bijgedragen aan meer inzicht in invloed en samenwerking binnen configurationele innovatiesystemen, ook meer inzicht te creëren van samenwerking op een breder niveau en om conclusies te trekken over hoe actoren een sterker samenwerkingsverband kunnen opbouwen om zo duurzaamheidstransities in een stroomversnelling te krijgen. Hiervoor wordt literatuuronderzoek van de Advocacy Coalition Framework (ACF) gepresenteerd. De ACF is een van de meest toonaangevende frameworks naar beleidsprocessen en beargumenteert dat beleidsprocessen grotendeels worden vormgegeven door collectieve groepen die samenwerken en daardoor de resultaten van het beleidsproces beïnvloeden. Terwijl de fundamentele notie van het ACF is dat actoren tot elkaar worden aangetrokken door dezelfde overtuigingen, schetst het literatuuronderzoek een genuanceerder beeld. Naast dezelfde overtuigingen speelt ook vertrouwen een grote rol en actoren lijken er meer toe te zijn geneigd om samen te werken door een aantal andere motieven, waaronder de drang naar politieke macht, toegang tot hulpmiddelen, en toegang tot de competentie van andere actoren.

Verder komt uit het literatuuronderzoek naar voren dat een essentiële vereiste voor samenwerking is dat actoren de mogelijkheid moeten hebben elkaar te ontmoeten en om te gaan met elkaar. Zo'n mogelijkheid kan bijvoorbeeld tot stand komen door een bepaalde invloed. Op basis hiervan – alhoewel het aanvankelijk leek dat actoren met dezelfde overtuigingen vanzelf naar elkaar toe zouden trekken, stelt deze nieuwe hypothese dat samenwerking niet vanzelf gebeurt en dat invloed kan worden gezien als een faciliterende factor, met name in het begin. Deze nieuwe visie op samenwerking heeft ook implicaties voor de ontwikkeling van configurationele TIS. Aangezien de structuur van de actoren in generieke TIS-systemen waarschijnlijk compact is, zorgt het ervoor dat actoren elkaar ontmoeten op bijvoorbeeld business meetings of tijdens politieke bijeenkomsten. Oftewel, in dergelijke systemen is het waarschijnlijk dat tussenpersonen kunnen helpen om de samenwerking te institutionaliseren, maar ze zullen niet dermate van belang zijn zoals bij configurationele TIS-systemen. Integendeel zelfs, actoren in configurationele TIS-systemen zullen waarschijnlijk niet van elkaars bestaan afweten en ook niet van plekken waar ze elkaar zouden kunnen ontmoeten los van geografische en bestuurlijke niveaus. Oftewel, we kunnen de conclusie trekken dat de behoefte aan tussenpersonen met een goed netwerk die voor bijeenkomsten kunnen zorgen waar kennis uitgewisseld kan worden en kan worden genetwerkt waarschijnlijk veel hoger is binnen configurationele dan binnen generieke TIS-systemen. Naast het bijdragen aan meer inzicht in samenwerking en coördinatie biedt het literatuuronderzoek een model van samenwerking en interactie dat aanknopingspunten biedt voor vervolgonderzoek en een aantal praktische aanbevelingen voor hoe coalities met impact gebouwd kunnen worden.

De conclusie van de thesis luidt dat contextafhankelijkheid een belangrijke factor is die meegenomen zou moeten worden bij het bestuderen van en beïnvloeden van duurzaamheidstransities. Het heeft overduidelijk een impact op de dynamiek van verandering en op het bemiddelen van actoren, omdat het coördineren van een gezamenlijke strategie en gezamenlijke acties veel moeilijker is. Het framework van configurationele innovatiesystemen kan helpen om de dynamiek van transities te begrijpen in situaties waar de lokale context een belangrijke rol speelt en om zo de snelheid van transities te verklaren. Deze invloed van de lokale context is ook een key explanatory variable om de onderzoeksvraag te beantwoorden waarom de Duitse warmtetransitie zo veel langzamer verloopt dan de transitie naar hernieuwbare elektriciteit.

Wissenschaftliche Zusammenfassung

Die Energiewende wird als gelungenes Projekt angesehen, da sie das deutsche Energiesystem relativ schnell dekarbonisiert. Deutschland nimmt seine Atomreaktoren außer Betrieb, setzt auf erneuerbare Energien und Energieeffizienz, und hat eine Strategie zum Kohleausstieg festgelegt. Der Fokus der Energiewende lag bisher jedoch auf der Transformation des Stromsektors, während die Energiewende in anderen Sektoren wie z.B. dem Wärmesektor nur langsam voranschreitet. Dies ist angesichts der Ähnlichkeiten zwischen Wärme- und Stromsystem überraschend, da beide Systeme in weitgehend ähnliche nationale, geografische, politische, gesellschaftliche und institutionelle Umgebungen eingebettet sind.

Die beobachteten Entwicklungsunterschiede werden in dieser Dissertation im Hinblick auf die folgende zentrale Forschungsfrage thematisiert: Warum können sich Transitionen in sehr ähnlichen Sektoren mit sehr unterschiedlichen Geschwindigkeiten vollziehen?

Diese Arbeit stützt sich auf interdisziplinäre Konzepte aus dem Bereich der Nachhaltigkeitstransitionsforschung. In der ersten Hälfte der Arbeit liegt der Fokus auf der Analyse der strukturellen Eigenschaften des deutschen Wärmesystems. Dieser Teil enthält zwei qualitative Interviewstudien. In der ersten Studie wird die deutschen Wärmewende mit der deutschen Elektrizitätswende verglichen, während in der zweiten Studie mit Wärmenetzen auf eine spezifische Wärmeversorgungstechnologie herangezoomt wird. Die zweite Hälfte der Arbeit konzentriert sich darauf, zu einem besseren Verständnis beizutragen, wie Akteur*innen ihre Wirkungskraft nutzen können, um Nachhaltigkeitstransitionen zu beschleunigen, und was sie dabei behindert. Hierzu wird in der dritten Studie dieser Dissertation mit Netzwerkdaten und qualitativer Interviews die Interaktion und Koordination zwischen Technologielobbygruppen analysiert und in der letzten Studie eine Literaturanalyse vorgestellt, die zusammenträgt, welche Faktoren Akteurs-Koordination beeinflussen und welche Schritte Akteur*innen wählen können, um sich kollektiv für Nachhaltigkeitstransitionen einzusetzen.

Der zentrale Ansatz, der im ersten Teil dieser Dissertation genutzt wird, ist der Technologische Innovationssystem (TIS)-Ansatz. Der TIS-Ansatz ermöglicht eine umfangreiche Systemanalyse der Entstehungs- und Diffusionsdynamik technologischer Innovationen. Basierend auf solchen Analysen können Erkenntnisse darüber gewonnen werden, was die Diffusion von Innovationen

behindert und welche Maßnahmen ergriffen werden können, um sie zu stimulieren. Da eine Schlüsselbedingung für Nachhaltigkeitstransitionen die Diffusion von Innovationen ist, die Güter und Dienstleistungen nachhaltiger bereitstellen können als dies aktuell der Fall ist, ist es im Rahmen dieser Arbeit zielführend, den diffusionsfokussierten TIS-Ansatz zur Beantwortung der Forschungsfrage dieser Arbeit zu verwenden.

Mit dem TIS-Ansatz werden in der vorgelegten Arbeit die strukturellen Besonderheiten des deutschen Wärme- und Stromsektors analysiert. Ohne Anpassungen des TIS-Ansatzes ist die langsame deutsche Wärmewende jedoch nicht hinreichend zu verstehen. Eine wichtige Erkenntnis dieser Arbeit ist, dass die Wärmewende stark vom lokalen Kontext beeinflusst wird, in dem die Implementierung neuer Technologie stattfindet. Da Wärme nicht kostengünstig transportiert werden kann, sind Erzeugung und Wärmebedarf stark geografisch gekoppelt und Wärmeerzeugungskapazitäten müssen somit immer lokal installiert werden. Aufgrund dieses Bedarfs an lokaler Umsetzung beeinflusst der lokale Kontext die Auswahl und Umsetzung von Wärmeerzeugungskapazitäten maßgeblich. Da jedes Gebäude einzigartig ist, muss jedes neu installierte Heizsystem speziell auf die örtlichen Gegebenheiten abgestimmt werden. Da Strom hingegen kostengünstig über weite Strecken über Stromnetze transportiert werden kann, sind das Stromangebot und Nachfrage geografisch entkoppelt, sodass die Umsetzung dort erfolgen kann, wo es am einfachsten und günstigsten ist. Die Implementierung von Stromtechnologien wie Windkraftanlagen und Photovoltaik-Modulen erfordert weniger spezifische Anpassungen an den lokalen Kontext. Deshalb können sie effizient in Serie produziert werden.

Basierend auf diesen Erkenntnissen werden Heiztechnologien in dieser Arbeit als konfigurative Technologien und Stromtechnologien als generische Technologien bezeichnet. Unter Ausnutzung dieser Differenzierung führt diese Dissertation den Begriff konfigurativer Innovationssysteme ein, die sich um konfigurative Technologien entwickeln (konfigurative TIS), und generische Innovationssysteme, die sich um generische Technologien entwickeln (generische TIS). Die Dissertation erweitert das Wissen über TIS, indem sie zeigt, dass sich konfigurative TIS wahrscheinlich langsamer entwickeln als generische TIS.

Die Differenzierung zwischen konfigurativen Technologien und generischen Technologien ist relativ. Dies bedeutet, dass ein TIS immer nur im Vergleich zu einem anderen als eher konfigurativ oder generisch eingestuft werden kann und kein TIS als perfekt generisch oder perfekt konfigurativ bezeichnet werden kann. Nichtsdestotrotz hat diese Differenzierung Auswirkungen auf die tragenden Säulen und Schlüsselprozesse technologischer Innovationssysteme: Konfigurative TIS weisen aufgrund ihrer stärkeren lokalen Kontextabhängigkeit stärker fragmentierte Akteursstrukturen, Interaktionen und Institutionen auf. Die in der Dissertation präsentierte empirische Evidenz legt nahe, dass konfigurative TIS aufgrund dieser stärker fragmentierten Struktur anfälliger für problematische Entwicklungsmuster sind, die eine schnelle Verbreitung nachhaltigerer Innovationen sowie Transitionen insgesamt behindern. Da beispielsweise bei der Installation neuer Heiztechnologien mehr lokale Kontextualitäten berücksichtigt werden müssen, können diese Technologien nicht so standardisiert werden wie Elektrizitätstechnologien, was wiederum weniger Raum für die Entstehung dominanter Designs lässt. Der Vorteil der Entstehung dominanter Designs ist, das Produkte mit solchen Designs von einer kleinen Anzahl an Herstellerunternehmen in großem Maßstab produziert und implementiert werden können, wodurch Synergien gehoben werden können. Aufgrund der durch dominante Designs entstehenden Vorteile (wozu beispielsweise Kostendegressionen gehören) können generische Technologien über die Zeit günstiger hergestellt werden, als dies bei konfigurativen Technologien der Fall ist. Darüber hinaus hat sich aufgrund unterschiedlicher lokaler Kontexte eine hohe Diversität an unterschiedliche Heizlösungen herausgebildet (verschieden Arten von Wärmepumpen, Geothermie-, Biodiesel-, Biogas-, Holzhackschnitzel-, Pellet-Anlagen usw.), die jeweils von unterschiedlichen politischen Interessenvertretungsorganisationen vertreten und beworben werden. Diese recht unterschiedlichen Akteursgruppen zu vereinen, um die Entstehung von Legitimität zu erleichtern und einen klaren und finanziell unterstützenden politischen Rahmen zu schaffen, ist schwieriger als dies bei der kompakteren Gruppe im generischen Strom-TIS der Fall ist.

Die Unterscheidung zwischen konfigurativem TIS und generischem TIS wird im Rahmen dieser Dissertation in zwei Studien entwickelt. Während die erste Studie den Begriff des konfigurativen TIS entwickelt und die Entwicklung des konfigurativen deutschen Wärme-TIS mit dem generischen deutschen Strom-TIS vergleicht, konzentriert sich die zweite Studie auf Fernwärmesysteme als eine spezifische Form konfigurativer Technologie.

Die Entwicklung von TIS wird nicht nur durch den systemischen Charakter von Innovationssystemen beeinflusst, sondern auch durch die Art und Weise, wie Agent*innen ihre Handlungsfähigkeit nutzen. Darüber hinaus kann erwartet werden, dass die Systemunterschiede zwischen generischem TIS und konfigurativem TIS Einfluss auf den Kontext haben, in dem Agenten in diesen Systemen arbeiten. Aus wissenschaftlicher Sicht ist es daher interessant, ein besseres Verständnis dafür zu entwickeln, wie Agenten in konfigurativen Umgebungen agieren. Während sich demnach der erste Teil der Arbeit auf die Einführung und Konkretisierung des Konzepts konfigurativer Innovationssysteme konzentriert, rückt der zweite Teil der Arbeit die Akteur*innen in den Mittelpunkt und konzentriert sich auf deren Handlungsfähigkeit in konfigurativen TIS.

In einer dritten empirischen Studie wird dementsprechend das Koordinationsverhalten industrieller Interessenvertretungsgruppen analysiert, die eine Reihe unterschiedlicher Heizlösungen unterstützten. Die Ergebnisse zeigen, dass die fragmentierte Struktur von Konfigurationssystemen nicht nur die systemischen Entwicklungsmuster, sondern auch die Handlungsfähigkeit und Koordination zentraler Akteursgruppen maßgeblich beeinflusst. Aufgrund einer stärker fragmentierten Akteursstruktur müssen in konfigurativen Systemen eine größere Anzahl unterschiedlicher Interessen und Visionen koordiniert werden. Eine solche Vielfalt an Interessen und Visionen schadet der TIS-Entwicklung grundsätzlich nicht, macht die Koordination der involvierten Akteur*innen aber aufwändiger. Im Ergebnis zeigt sich aufgrund der großen Vielfalt an Interessen und Visionen, dass im konfigurativen TIS vergleichsweise viele kleine Koalitionen entstehen können. Die Analyse von Netzwerkdaten und qualitativer Interviewdaten deutet darauf hin, dass die Zusammenführung dieser diversen Gruppen zu einer einzigen und schlagkräftigen Koalition in konfigurativen TIS eine Herausforderung darstellt.

Nachdem die Dissertation mit der dritten vorgestellten Studie zu einem tieferen Verständnis von Koordination in konfigurativen Innovationssystemen beigetragen hat, zielt die Arbeit in der letzten Studie darauf ab, zu einem besseren Verständnis von Koordination auf einer breiteren Ebene beizutragen und Schlussfolgerungen darüber zu ziehen, wie Akteur*innen stärkere Koalitionen bilden können, um Nachhaltigkeitstransitionen zu beschleunigen. Dazu wird eine Literaturrecherche des Advocacy Coalition Framework (ACF) vorgestellt. Das ACF ist eine der etabliertesten politischen Prozesstheorien und argumentiert, dass der politische Prozess wesentlich von kollektiven Gruppen geprägt wird, die durch ihre Koordination und Nutzung ihrer Ressourcen die Ergebnisse des politischen Prozesses beeinflussen. Während die Grundidee des ACF darin besteht, dass Akteure sich aufgrund ähnlicher Überzeugungen zusammenfinden, zeichnet die auf einer breiten Literaturanalyse basierte Studie ein differenzierteres Bild. Neben ähnlichen Überzeugungen spielt auch Vertrauen eine große Rolle, und Akteure scheinen von einer Reihe anderer Faktoren motiviert zu sein, sich zu koordinieren, wie etwa dem Drang nach politischer Macht, dem Zugang zu Ressourcen und dem Zugang zur Kompetenz anderer Akteure. Darüber hinaus legen die Ergebnisse der Literaturrecherche nahe, dass eine grundlegende Voraussetzung für eine erfolgreiche Koordination darin besteht, dass die Akteure die Möglichkeit haben, sich zu treffen und miteinander zu interagieren. Solche Möglichkeiten können beispielsweise Koalitionsbroker bieten. Diese neue Sichtweise der Koordination hat auch Auswirkungen auf die Entwicklung konfigurativer TIS und generischer TIS. Da die Akteursstruktur im generischen TIS eher kompakt ist, erleichtert sie es den Akteuren, sich zu treffen, beispielsweise bei Branchentreffen oder durch politische Dialoge. Daher sind Broker in solchen Systemen wahrscheinlich in der Lage, Koalitionen bei der Institutionalisierung zu helfen, aber sie sind möglicherweise nicht so grundlegend wichtig wie in konfigurativen TIS. Im Gegensatz dazu wissen die Akteur*innen in konfigurativen TIS weniger wahrscheinlich voneinander oder von Orten, an denen sie sich treffen können, beispielsweise über geografische und administrative Ebenen hinweg. Zusammenfassend lässt sich sagen, dass der Bedarf an gut vernetzten Brokern, die Orte für Austausch und Vernetzung organisieren und bereitstellen, bei konfigurativen TIS wahrscheinlich wesentlich höher ist als bei generischen TIS. Basierend auf der Literaturrecherche wird schließlich ein Modell der Koalitionsinteraktion vorgeschlagen, dass eine Reihe praktischer Empfehlungen zum Aufbau wirkungsvoller Koalitionen macht und mögliche neue Forschungsfelder eröffnet.

Die Arbeit kommt zu dem Schluss, dass Kontextabhängigkeit ein wichtiger Faktor ist, der bei der Untersuchung und Beschleunigung von Nachhaltigkeitstransitionen berücksichtigt werden sollte. Sie wirkt sich eindeutig auf die Wandlungsdynamik und die Handlungsfähigkeit der Akteur*innen aus, da die Koordination von Strategien und Aktionen in stark kontextabhängigen Systemen schwieriger ist. Das Konzept der konfigurativen Innovationssysteme kann hilfreich sein, um sowohl Transitionsdynamiken in Situationen zu erfassen, in denen der lokale Kontext eine wichtige Rolle spielt, als auch Geschwindigkeiten von Transitionen zu erklären. Der Einfluss des lokalen Kontexts ist auch ein wichtiger Erklärungsfaktor für das deutlich langsamere Voranschreiten der deutschen Wärmewende im Vergleich zur Transition des deutschen Elektrizitätssystems.

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Deep thanks to my kjæreste and future wife Lillian for laughter, joy and adventures on the way here and the road ahead.

The thesis introduces the concept of configurational innovation systems as a subtype of technological innovation systems. Configurational innovation systems evolve around technologies that are highly dependent on the local context for their implementation. The thesis introduces the concept of generic innovation systems as a counterpart of configurational innovation systems, which evolve around technologies that are less dependent on the local context for their implementation. The differentiating between configurational innovation systems and generic innovation systems is relative in terms of scale, yet it has repercussions for the defining pillars and key processes of technological innovation systems. Due to their stronger local context dependence, configurational innovation systems feature more fragmented actor structures, interaction, and institutions. The empirical evidence from the German heat sector, which is presented in the thesis, suggests that due to this more fragmented structure, configurational innovation systems are prone to problematic development patterns. These hinder supportive policy change and hence slow the rate of diffusion of more sustainable innovations, as well as of sustainability transitions more generally.

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