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Configurational innovation systems – Explaining the slow German heat transition

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ABSTRACT

In the field of sustainability transitions, temporality has recently received increased attention, specifically with regard to understanding acceleration of transitions. Acceleration of sustainability transitions is needed, to minimize the risks of global crises, and so the question is how these transitions can be accelerated. To answer this question, we use the technological innovation systems (TIS) approach to better understand the underlying processes. The central argument of this paper is that the pace of development in TIS, which ultimately have an impact on sustainability transitions, strongly depends on the local context in which the technologies are embedded in.

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 – in this paper we refer to these as generic technologies. Conversely, technologies that are strongly dependent on the local context always need to be configured with regard to specific local contingencies – we refer to these as configurational technologies. This differentiation has repercussions on the defining pillars of technological innovation systems: Higher local context dependence slows down the pace of development of configurational TIS. The differentiation is illustrated by comparing electricity and heat innovation systems in Germany. An analysis based on literature as well as empirical case studies shows that the rather generically structured Solar PV and onshore wind are developing faster toward decarbonization than the configurationally structured heat TIS. The distinction between generic technological innovation systems and configurational technological innovation systems is helpful to better understand innovation system development and design supportive policies.

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 [1–7]. 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 [8–10]. Their performance can be analyzed through so-called system functions [11]. 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 [9,12–15].

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 [16], (2) the mode of valuation [17,18] and (3) the mode of innovation and knowledge generation [18]. Especially Binz and Truffer [18] call for a "greater emphasis on the role of multi-scalar networks and systematic differences between the innovation processes in various industries" [18,p. 1284].

Regarding these differentiations we see two research needs. First, the differences exemplified so far have not yet been linked to the

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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 [18,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 [19,20], 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 these 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 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 all across Central Europe, we deem this approach justifiable and helpful to understand the general influence of diverging local context dependence.

2. Conceptualizing generic and configurational TIS

2.1. 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 [21,22][21, p. 956, 22, p. 12]. Recently, much more attention has been paid to the temporality or pace of transitions [1–7]. 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 [23,p. 5,24] 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 fulfill societal functions.

Over the last three decades, different variations of innovation systems have been conceptualized and applied empirically. These include the concepts of national [25], regional [26], sectoral [27] and technological [8] 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" [18,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 [8–11]. Actors are delineated into categories (individuals, organizations, and networks) based on their role in economic activity: civil society, government, non-governmental organizations (NGOs), companies, knowledge institutions, and other parties [10,p. 76]. Interactions can take place within networks or between individuals [10,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" [10,p. 76,28]. According to Wieczorek and Hekkert [10], infrastructure encompasses three categories: physical, financial and knowledge [10,p. 77]. Physical infrastructure includes artifacts, instruments, machines, etc.; financial infrastructure comprises subsidies, financial programs, and grants; and knowledge infrastructure encompasses knowledge, expertise and strategic information [10,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 1). "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" [12,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 [11,29,30][11, p.426, 29, p. 272, 30, p. 422].

Scholars studying the dynamics of innovation systems have discovered that distinct functional patterns occur at different stages of TIS development [30]. 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 [30,31,32][30, p. 420, 31, p. 819, 32, p. 926].

The formative phase is marked by many uncertainties [33,p. 577] and "sets up the conditions for a technology to emerge and become established in the market" [34,p. 95]; see also [35]. It is further characterized by "a range of competing designs, small markets, many entrants and high uncertainty in terms of technologies, markets and regulations" [31,32][31, p. 819, 32, 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" [30,p. 420]. The formative phase can be a very lengthy phase – easily two or three decades – [34], and thereby slow down transition processes. Also, during the diffusion phase large differences in diffusion speeds are reported [4,6]

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 [10,36–39]). Up until now, not much conceptualization has been done

[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.

Table 1
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. [82,p. 12] based on Hekkert et al. [11].

to understand whether specific characterizations of a TIS impact the length of the formative and diffusion phase.

2.2. 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. [15] 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 [16] and second, the type of innovation and knowledge generation processes [17,18].

Regarding the types and number of sectors linked via the value chain [16] 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 [17] 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 [18] 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 [18] 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.

2.3. 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 [19] 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 [19] distinguishes between generic and configurational technologies by applying five dimensions which we expand via other literature in the following:

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 [19,pp. 17–18]. It reflects what [40–42] 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” [19,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 toward dominant designs and standardized plans [43]. Fleck calls this process crystallization. Configurational technologies, on the other hand, are unlikely to shape such clear crystallizations since “local

[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.

contingencies continue to resist stabilization or crystallization" [19,p. 29]. Purely configurational technologies need to adapt their components architecture [44] to the local contingencies. While generic technologies can reach a dominant design on a system level by crystallizing a specific component architecture due to the existence of standard plans [19,pp. 28–29]. Configurational technologies can only reach dominant designs on the component level [45,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" [19,p. 18]. This is in line with Lee and Berente [46] 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" [19,47][19, p. 19, 47, 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 [19,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" [19,p. 28]. Fleck describes this phenomenon as 'innofusion', since "process(es) of innovation and diffusion are collapsed together" [19,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 [19] 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 [19] 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. [15] 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 et al. [17]. 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 [18]. 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" [18,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 (Fig. 5). 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) [48], 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.

3. Methodology

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

Table 2
Theoretically-derived characteristics of generic and configurational technologies adopted from Fleck [19].

	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 toward 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.

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: [14,29,31,49–55]. 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 keywords: "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. 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 [56].

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 labeled with MAXQDA using categories derived from Tables 1 and 2. In order to reach intercoder 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.

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.

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

The pace of transition toward 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 meager. 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 (Fig. 1, line 1 – gray).

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.

4.1.1. 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 [57,S. 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 [50,51,58–60]. 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 [58,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.

[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).

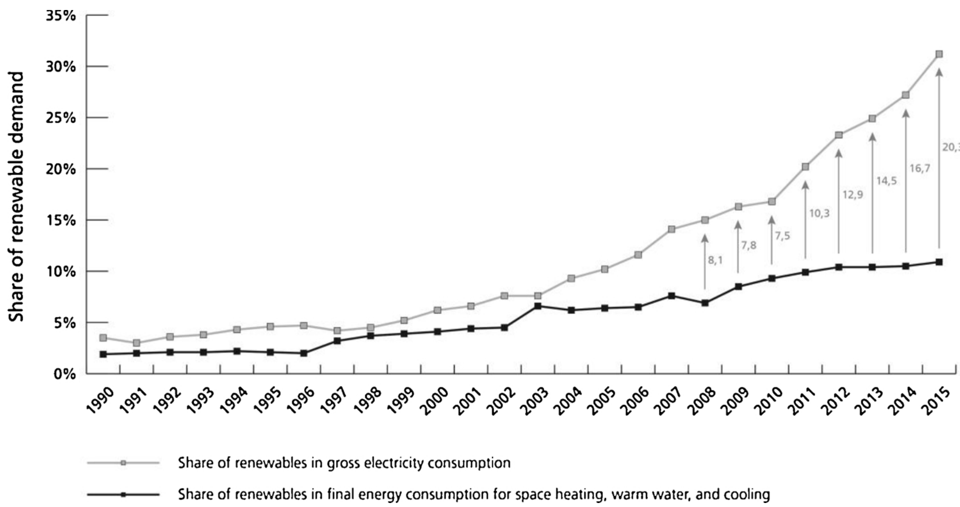

Fig. 1. Shares of renewable energy in gross electricity consumption and share of renewables in final energy consumption for space heating and warm water heating (and cooling) ([57] and Anwendungsbilanzen 2011/2012 and 2016).

Therefore, most knowledge generation takes place upstream and communication is rather one-directional, flowing from upstream to downstream [51,61][51, 61, 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] .

4.1.2. 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 [62,63][62, p. 16, 63, p. 3] 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 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 [64,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.

4.1.3. 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 Fig. 2, 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 [29,p. 263]. After a long-fought battle for legitimacy that was often conducted by community initiatives [29,51], 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 and Wilson [34,p. 102] and Dewald and Fromhold-Eisenbith [53,p. 117]. Bento and Wilson [34,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-Eisenbith [53,p. 117] specifically suggest 2004 as the year the transitions happened for Solar PV. We do acknowledge that pinpointing a specific year

[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.

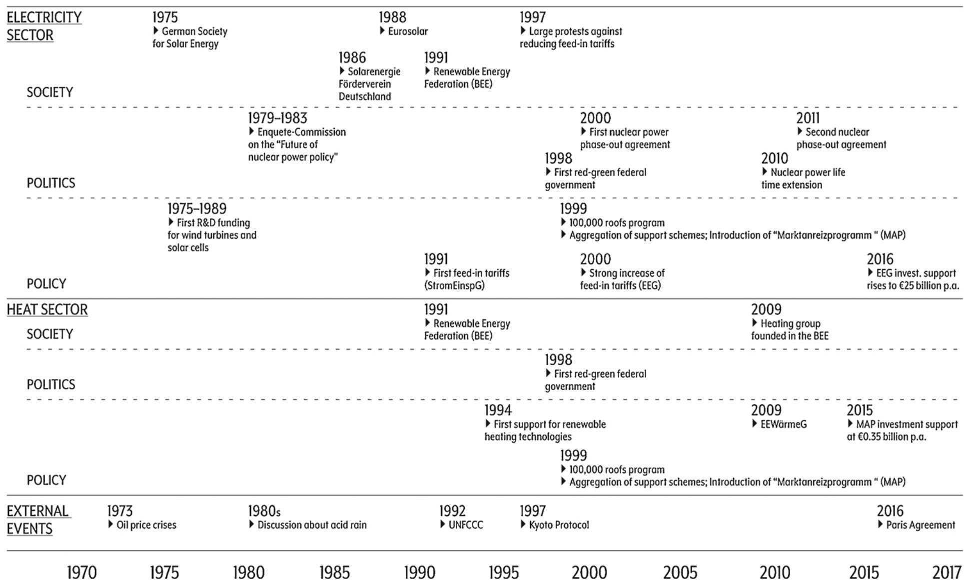

Fig. 2. Timelines of the electricity and heat transition in Germany.

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 (Fig. 1); (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).

4.2. 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 et al. [11]. 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 (Fig. 5) 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.

4.2.1. Structural comparison

4.2.1.1. 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 (Fig. 3).

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 (Fig. 4). 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 [65]. 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)

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.

4.2.1.2. 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

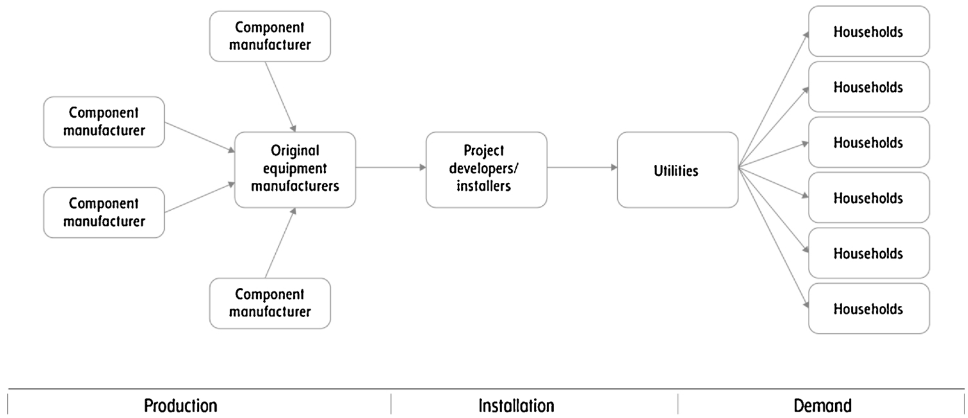

Fig. 3. Structure of core actors for generic technologies such as onshore wind farms and (partly) roof top solar PV.

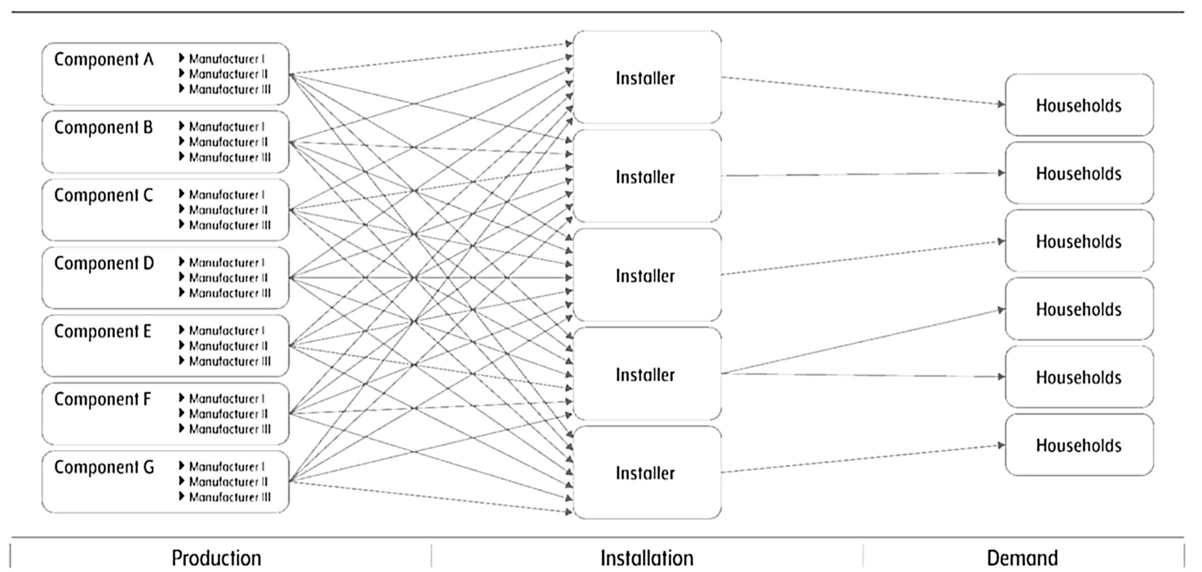

Fig. 4. Structure of core actors for context dependent technologies such as single house heating solutions or heat grids, but also special types of wind farms (low-speed or high-altitude wind farms).

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 [29,50,51][29, p. 272, 50, p. 605, 51, p. 292]. On the national level, several more formalized networks were established to promote solar energy in Germany [14,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]

4.2.1.3. 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 TISs managed to implement a continuous stream of new and ever growing support schemes (Figure 2, [14,31,52][14, p.17, 31, p. 833, 52, p. 17]), which culminated

[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 [66,p. 3].

eventually in the enactment of the German Renewable Energy Sources Act (EEG) (see Fig. 2). 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.

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)

4.2.1.4. 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.

4.2.2. Functional comparison

4.2.2.1. 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 [67]. 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. [29,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 [68,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.

4.2.2.2. 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.

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

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

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.

4.2.2.3. 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 [29,51,52,54][29, p. 263, p. 266, 51, p. 292, 52, p. 408, 54, p. 902]. 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 [69]. 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.

4.2.2.4. 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) [29,p. 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 [29,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 [70,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 [68,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.

4.2.2.5. 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" [29,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 [29,50,51][29, p. 265, 50, p. 617, 51, p. 298]. This legitimacy in combination with a growing number of employees probably led to the implementation of the "1000 Roofs Program", the first feed-in-tariff in 1990, the "100,000 Roofs Program" in 1999 and the "market creation with a punch" [55,p. 150] due to the implementation of the EEG that secured an attractive funding base for private and institutional investors (cf. [29]).

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.

4.2.2.6. 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) [29,p. 261]. In 2016, approximately 202 million euros were invested in R&D for solar PV and wind energies alone (excluding grids

Table 3
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.	Configurational TIS are by default influenced by a greater variety of (incumbent) infrastructures since these are part of the local context.

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.

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 [29,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” [29,p. 267,71,p. 164,72,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 [73,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) [74,75].

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.

4.2.2.7. 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” [76,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” ([33,p. 581] e.g. [77–79]). 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) [76, p. 576]. In the case of strong alignment, organization(s) can genuinely reach out to specific resources made available by society [76,p. 576]. 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 organizations (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” [76,p. 592].

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 [29,50][29, p. 265, 50, p. 617]. While the nationwide organization focused on lobbying for new policy edicts [29,p. 264], “the green movement articulated demand for decentralised technology” [51,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 [54]. The strong actor coalition made it possible to gain increasing policy support which finally resulted in the enactment of the EEG [29,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 [52,54,80][52, p. 409, 54, p. 910, 80], 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

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

Table 4
Comparison of the system functions' fulfillment 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.
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.

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.

Tables 3 and 4 summarize the findings of the comparison in a condensed and abstract way.

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

4.3. 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 toward 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

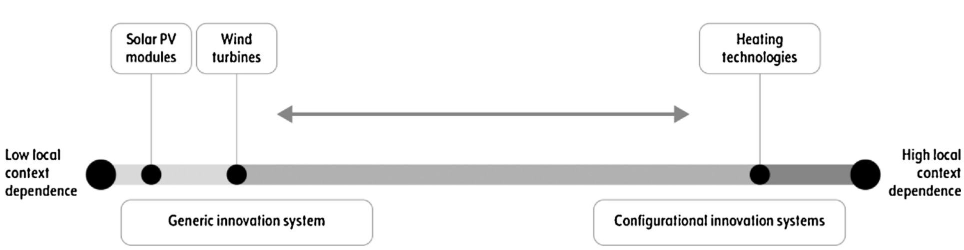

Fig. 5. Technological innovation system on a context dependence scale.

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.

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 (Fig. 5). 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 [19,p. 34], but is nevertheless helpful for analysts.

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 [12,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 toward 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 [15,81], 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 [80]. 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.

Appendix A. Appendix

Table 5
Interviews conducted.

Number	Position	Affiliation	Date
1	Mayor	Project #1	June 2016
2	CEO of project developer	Project #1	June 2016
3	Project manager of project developer	Project #1	June 2016
4	Leader of local environmental group	Project #1	June 2016
5	CEO of local waste heat supply company	Project #1	June 2016
6	Former head of local energy agency	Project #1	June 2016
7	CEO of local heating oil supply company	Project #1	June 2016
8	Local civil servant and co-initiator	Project #2	June 2016
9	CEO of local renewable energy company and co-initiator	Project #2	June 2016
10	Mayor	Project #2	June 2016
11	Former mayor	Project #2	June 2016
12	CEO of tech provider and project developer	Project #2	June 2016
13	Researcher at local technical college	Project #2	July 2016
14	Manager from national utility company	Project #2	July 2016
15	Initiator and member of local parliament	Project #3	July 2016
16	City counselor	Project #3	July 2016
17	City project manager	Project #3	July 2016
18	CTO of local utility company	Project #3	July 2016
19	Vice president strategy of local utility company	Project #3	July 2016
20	Mayor and co-initiator	Project #4	June 2016
21	CEO of local agri-enterprise and co-initiator	Project #4	June 2016
22	Member of executive board of local energy cooperative and co-initiator	Project #4	June 2016
23	Mayor	Project #5	July 2016
24	CEO of local heat technology enterprise and co-initiator	Project #5	July 2016
25	CEO of local software enterprise and co-initiator	Project #5	July 2016
26	Former CEO of local utility company and initiator	Project #6	August 2016
27	Civil servant in state treasury ministry and project manager	Project #6	August 2016
28	Civil servant in regional construction authority and project manager	Project #6	September 2016
29	Energy researcher	Expert	May 2016
30	Representative of specific heat tech association	Expert	July 2016
31	Representative of renewable energy association	Expert	July 2016
32	Representative of heat technology think tank	Expert	August 2016
33	Representative of fossil heat tech campaigning group	Expert	August 2016
34	Representative of national chimney sweeper association	Expert	August 2016
35	Manager at integrated heat technology incumbent	Expert	August 2016
36	Heat related project manager of state level energy agency	Expert	November 2016
37	Manager at a pipe tech company	Expert	November 2016

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