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Heat pumps in the existing Dutch housing stock: An assessment of its Technological Innovation System

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ABSTRACT

Heat pump technology has the potential to substantially increase the efficiency of domestic space heating which is currently based on boiler technology. Although the heat pump has reached technological maturity, its implementation remains hampered by numerous non-technological barriers in many countries. This paper presents an assessment of the barriers that hamper diffusion of heat pumps in the Dutch residential sector. For this purpose, the state of its Technological Innovation Systems (TIS) was assessed. Particular attention was thereby given to the role of the sectoral context as this is where the heat pump ultimately needs to fit in. The success of domestic heat pumps was found to be highly dependent on how developments within the sectoral context unfold. The findings not only present what is hampering domestic heat pumps in the Netherlands, but also show that the sectoral context can be much more dynamic than literature suggests.

Introduction

The residential sector is responsible for 17% of global CO_2 emissions, of which 1.9 Gton direct emissions from combusting fossil fuels for space heating and hot water, and 3.7 Gton indirect emissions from upstream electricity and heat generation [13]. To keep average global temperature rise below 2 or even 1.5 °C, emission reductions are thus needed in this sector, both in end-use and upstream activities. However, the IEA [14] indicates that current global policies are insufficient for reaching strong emission reductions. This is also found true for Europe where especially the existing housing stock is considered a major challenge [9]. Namely, current levels of energy retrofits are lower than needed [25] and an emphasis on shallow renovations may result in a so-called efficiency gap [31].

In the Netherlands, electric heat pumps are seen as important means to increase the efficiency of domestic space heating since most Dutch houses are currently heated by natural gas-fired boilers. In Europe, Sweden, Estonia, Finland and Norway already have well-developed heat pump markets [8]. Although the market for heat pumps in the existing Dutch housing stock is growing, the size of the market is still small. Between 2014 and 2018 the amount of heat pumps sold for space heating in the existing housing stock increased from almost 4.000 annually to more than 24.000.[1] For comparison: the annual sales of natural gas-fired boilers in the Netherlands is still around 400.000. Assessing what is hampering a faster diffusion of heat pumps in the Dutch residential sector is a first step to reaching its high technical potential.

The Technology Innovation System (TIS) framework has proven a valuable tool to assess what hampers the development and implementation of a particular technology [1,7,10,12,16,17]. It is founded on the idea that – around the technology – a strong innovation system needs to develop for it to further develop and become implemented. During a TIS-analysis, weaknesses (also called systemic problems) are pinpointed that hamper the development of the innovation system developing around the technology under study. It thus provides a fitting choice for assessing what is hampering the heat pump for use in Dutch residential houses.

Although literature has always recognized that TISs are usually embedded in – and show overlap with – other systems (e.g. [20]), initial work mainly focused on understanding internal TIS dynamics [1,10]. In recent TIS research, the importance of taking contextual structures such as other TISs and sectors into account is particularly stressed [2]. For a technology with the characteristics of the heat pump, taking sufficient context into account is particularly imperative. First of all, there are

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[1] This includes only air-to-water heat pumps. Ground source heat pumps (2.000 in 2014 and 6.000 in 2018) are excluded since these are mainly used in newly built houses. Air-to-air heat pumps that are dominantly used for cooling alone (almost 40.000 in 2014 and 73.000 in 2018) are excluded as well (data from: [28]).

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multiple types of heat pumps available that aim to replace the yet dominant gas-fired boilers in existing houses (the particular Dutch context), of which the stand-alone heat pump and the hybrid heat pump[2] are most prominent in the Netherlands. Both of these technologies develop largely within their own respective Technological Innovation System. Second of all, both types of heat pumps show different types of interactions with other often used renovation technologies like insulation and solar panels. Each of these technologies is also developing within its own respective TIS. Finally, whether and how these technologies are combined within a renovation project is determined by actors that are part of the renovation sector.

Literature has so far been unclear about the role that contextual structures may play in the functioning of a particular Technological Innovation System. On the one hand, it is explained that contextual structures "[…] tend to change over time, both as a matter of autonomous developments in context structures and as a consequence of the focal TIS growing and becoming more mature" [1]. On the other hand, in relation to sectoral context structures specifically, it is mentioned that "A sector […] provides a quite stable context, which individual TISs either have to adapt to or try to change to their own benefit" [1]. In this paper, the role of relevant contextual structures will be particularly stressed, thereby focusing on the question what influence these contextual structures have had on the functioning of heat pump Technological Innovation Systems. Next to the theoretical contribution of analyzing the role of contextual structures in depth during a case study, this paper also provides insight into how this methodologically may be achieved.

In the Dutch political landscape relative stable periods are once in a while interrupted by periods of high change. In the spring of 2018, negotiations started for a Dutch Climate Agreement, the Dutch answer to the Paris Agreement. Exact consequences for heat pump related initiatives and subsidy programs in view of the Climate Agreement have however not yet materialized. Since the role of sectoral context cannot unambiguously be determined in a fast-changing policy environment, this study deliberately focuses on the relative stable policy period between 2012 and 2018. In this way, this paper works towards answering the following research question: What inhibited the implementation of heat pumps in the Netherlands between 2012 and 2018 and what was the influence of the sectoral context?

This paper proceeds as follows: the theory section provides an overview of existing literature on heat pump diffusion, it introduces the TIS-framework in more detail, describes the stages of a standard TIS-analysis and discusses how attention for TIS context can be conceptualized. Then, in the method section, the general TIS-analysis stages are adapted to explicitly incorporate TIS-context, followed by the results, discussion and conclusion sections.

Theory

Heat pump literature review

A rich body of literature exists that studies the diffusion of heat pumps in the residential sector. Bianco et al. [3] e.g. analyzed the primary energy and carbon savings when replacing domestic gas boilers by electric heat pumps in Italy. Neirotti et al. [22] and Bianco et al. [4] evaluated the impact of increased heat pump use on the energy and emissions performance of the electricity mix across Europe. Protopapadaki & Saelens [24] are representing a body of literature focusing on the impacts on the local electricity grid with increased electrification of the heat supply, in their paper specifically focusing on Belgium. Roy & Caird [26] investigated the interacting factors, both technical and non-technical (such as behavior-related), that affect heat pump efficiency. Xie et al. [35] particularly focused on the interaction of various technologies in a typical UK house (incl. heat pumps and solar technology) to identify potential for energy savings and assessing the financial aspects. Pezzuto et al. [23] carried out a SWOT analysis for the European heat pump market and identified a number of economic barriers: the price ratio between alternative energy sources and electricity, high investment costs, and higher installation costs. To the best knowledge of the authors no scientific study exist that attempts to explain the (lack of) diffusion of heat pumps in the existing housing stock in an integrative and holistic way, looking at technical, economic, and contextual factors such as sector characteristics.

TIS framework

The TIS framework was developed to assess how the development and diffusion of particular technological innovations may be stimulated. It does so by assessing whether the system around the technology is developing as it should. In innovation systems literature, it is generally recognized that Actors, Institutions and Interactions (sometimes called Networks) form the central building blocks or 'structural elements of the system (e.g. [15,19–21]). When the performance of an innovation system is unsatisfactory, this is likely caused by weaknesses that pertain to its structure. Conceptually, the term systemic problem[3] points at weaknesses in these structural elements [15,34]. A TIS-analysis leads to the identification of systemic problems for which solutions in the form of interventions can be formulated.

To identify systemic problems, it is common practice to combine an analysis of the system structure with an analysis of key processes, often called functions. Hekkert et al. [10] distinguishes between seven functions, namely 1) entrepreneurial activities, 2) knowledge development, 3) knowledge diffusion through networks, 4) guidance of the search, 5) market formation, 6) resources mobilization, and 7) creation of legitimacy/counteract resistance to change. Analyzing the fulfillment of these seven functions provides an indication of the innovation systems' performance, while the systemic problems are the reasons for why functions are not fulfilled well. The general process for performing an innovation systems analysis consists of several steps that include demarcating the system, describing the system structure, assessing the phase of development of the technology in focus, determining function fulfillment, identifying systemic problems, and formulating interventions to alleviate those problems [1,34]. Together, these steps form a so-called structural-functional analysis of an innovation system. In this paper, a structural-functional analysis is presented of heat pumps for use in Dutch residential houses.

TIS & phases of technology development

Assessing the phase of development of the technology is important, because their relative importance in each phase varies [30,11]. Roughly speaking, in the first phase (*predevelopment*), actors collectively develop knowledge and work toward a first prototype to provide evidence that the technology works. In this phase, the focus thus lies on the functions knowledge development (F2) and knowledge diffusion through networks (F3). The other functions provide support, for instance, a high potential for the technology should be emphasized (F4), so that resources are made available (F6) for knowledge development (F2). In the subsequent *development* phase, the technology is tested in pilot projects. The focus thus lies on the function entrepreneurial activities (F1) and, because these pilot projects are usually collective activities, on knowledge diffusion (F3). The main subject for knowledge development in this

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[2] The technical difference between the two is explained in detail in "Stage 1: Defining focal technology in the Dutch context".

[3] The terms systemic problem and blocking mechanisms [1] are both prominent in the technological innovation systems strand, whereas system failure is prominent in literature on innovation systems in general [19,33]. For a discussion of the conceptual link between these terms see Kieft et al. [17].

phase is making the theoretical knowledge gained in the first phase practically useful (F2). It is important that the technology is considered legitimate by sufficient actors (F7) so that sufficient resources can be mobilized to support the other functions (F6). Possibly, the technology is successfully introduced in a niche market (F5) which, together with a hopefully successful pilot project (F1), further stimulates actors to emphasize the necessity of the technology (F4). Then, in the *take-off* phase, the first pilot projects end (F1) and the effort to bring the technology to the market further increases (F5). This phase may be accompanied with strong resistance from outside the system, therefore requiring strong legitimacy creation (F7), which the hopefully successful pilot projects (F1) provide. The growing market (F5) stimulates actors to increase the expectations for the technology (F4) what may lead to additional and larger scale pilot projects (F1). Obviously, resources are required to support the other functions (F6), whereas knowledge development (F2) becomes less prominent during this phase. Subsequently, in the *acceleration* phase, the pilot projects (F1) move to the background as further stimulation of the market (F5) becomes the highest priority. Because the technology has proven its worth in the pilot projects, more actors begin to support the technology (F4) and, as a result of cost reductions (F6), diffusion accelerates. Finally, saturation is reached in the *stabilization* phase where the diffusion stabilizes. Since each phase of development requires the fulfillment of different functions, it is important to take the phase of development into account when judging whether function fulfillment in a particular system is ‘good’ or not.

TIS & contextual structure

Next to analyzing the internal dynamics of the TIS through a structural-functional analysis, the importance of involving relevant contextual structures has specifically been stressed by Bergek et al. [2]. They explain that interactions between a TIS and contextual structures can be of two kinds, namely external links and structural couplings. External links refer to dependencies of the TIS on its context. For example, the electricity law restricts the possibilities for connecting radically new energy generation technologies (e.g. blue energy) to the grid. Companies that develop these radically new technologies – and are thus part of the TIS – usually do not have the capacity to influence the electricity law. External links are thus one-directional from the context to the TIS. Structural couplings refer to ‘shared elements between a TIS and specific context structures” [2]. A case in point are fossil fuel companies that become active in wind energy and thus span multiple TISs. Because such companies often have better access to governments, they may be able to successfully lobby for changes to laws and regulations. Structural couplings are thus two-directional between the TIS and its context. In earlier development phases, TISs are mostly dependent on their environment (only external links), whereas in later development phases, the TIS will have more structural couplings.

According to Bergek et al. [2] a TIS can have external links and structural couplings with at least four contextual structures: 1) other TISs, 2) sectors, 3) geographical context structures, and 4) political context structures. Bergek et al. [2] explain that, depending on the purpose of the case study “we can focus on a particular context structure to investigate its dynamics and links to the focal TIS” (p. 61). In the case of the heat pump for use in Dutch residential houses, the most relevant contextual structures are other TISs as well as the sector. When a house is renovated, activities are rarely restricted to installing a heat pump only. Instead, there are usually multiple technologies installed (insulation, solar panels, heat pump etcetera), implying the importance of TIS/TIS interactions. Furthermore, the choice for installing a heat pump or not, and if so what type, is made at sectoral level as it depends much on how the renovation process is organized, and what other technologies are chosen for during the renovation process. TIS/sector interactions are thus also deemed important. The focus on one country (the Netherlands) makes the geographical dimension less relevant. The Netherlands is also unique in the sense that policies (and thus politics) in relation to the build environment (and thus heat pumps) are mainly set at national level, i.e. without regional differences. For the case study as presented in this paper, the Netherlands thus provides a shorthand denomination for the geographical and political dimensions, so that the focus may be placed on TIS/TIS and TIS/sector interactions.

Categorization of modes of interaction

The conceptual means to analyze TIS/TIS interactions are provided by the categorization of modes of interactions by Sandén and Hillman [27]. To begin with, technologies may be in *competition* with each other because they make use of a common resource or accommodate the same market. Technologies may also be in *symbiosis* because one technology benefits from the implementation of the other, and vice versa. Next, a situation of *neutralism* refers to two TISs that do not affect each other. *Parasitism* (and predation) materializes when technology 1 is benefiting technology 2, whereas technology 2 is inhibiting technology 1. Subsequently, *commensalism* describes a situation where one technology is benefited, while the other is not affected, and finally, *amensalism* happens when one technology is inhibited, while the other is not affected. The modes of interaction between two TISs is in line with the modes of interaction of their focal technologies. For instance, if two technologies compete, the actors within the two respective Technological Innovation Systems will also compete, or if two technologies interact through a commensalism relationship, actors within one TIS will try to collaborate with the other, whereas actors within the other TIS will not be bothered. The case study of the heat pump will make use of Sandén and Hillman’ categorization not only to describe the technology/technology interactions between heat pumps and other relevant technologies but also to describe the interactions between actors from the respective TISs.

The focus is placed on the most relevant TIS/sector interactions, namely the ones found to strongly influence the development of the heat pump TIS. It is important to understand that for most sectoral actors, the heat pump is not an end in itself, but rather a means to an end. For instance, housing associations, the national government and municipalities may be interested in reducing energy-use and increasing energy-production in residential houses, but for them it generally does not matter what technologies are utilized to achieve this goal. However, the ambition level of the goals does strongly influence what technologies make most sense to implement, and in this way goals thus influence whether the heat pump is chosen for or not. For instance, when renovating a house toward energy neutral, more and different technologies will be necessary than when the goal is to slightly improve the energy-efficiency of a house. We therefore focus on discussing main renovation goals that Dutch sectoral actors commonly strive for, and illustrate why, depending on the set goal, either a standalone heat pump, a hybrid heat pump or a high-efficient gas boiler will be preferred. We do not consider the pellet boiler in our analysis since this technology has not been widely used in the past in the country, and is only expected to play a marginal role in the heat transition. In the “Discussion” we discuss why district heating is excluded from our analysis.

Method

The standard TIS-analysis steps were adapted to incorporate more explicit attention for TIS-context. The method followed consisted of six stages, see Fig. 1.

During the first stage the focal technology was defined, in this case the heat pump. During the second analysis stage, the modes of interaction were analyzed between the heat pump and other renovation technologies like insulation, solar panels etcetera. The purpose of this stage was to gain insight into whether the heat pump is sufficiently independent from these other technologies to justify their separate analysis. The third analysis stage focused on the structural couplings between their respective Technological Innovation Systems to decide whether to

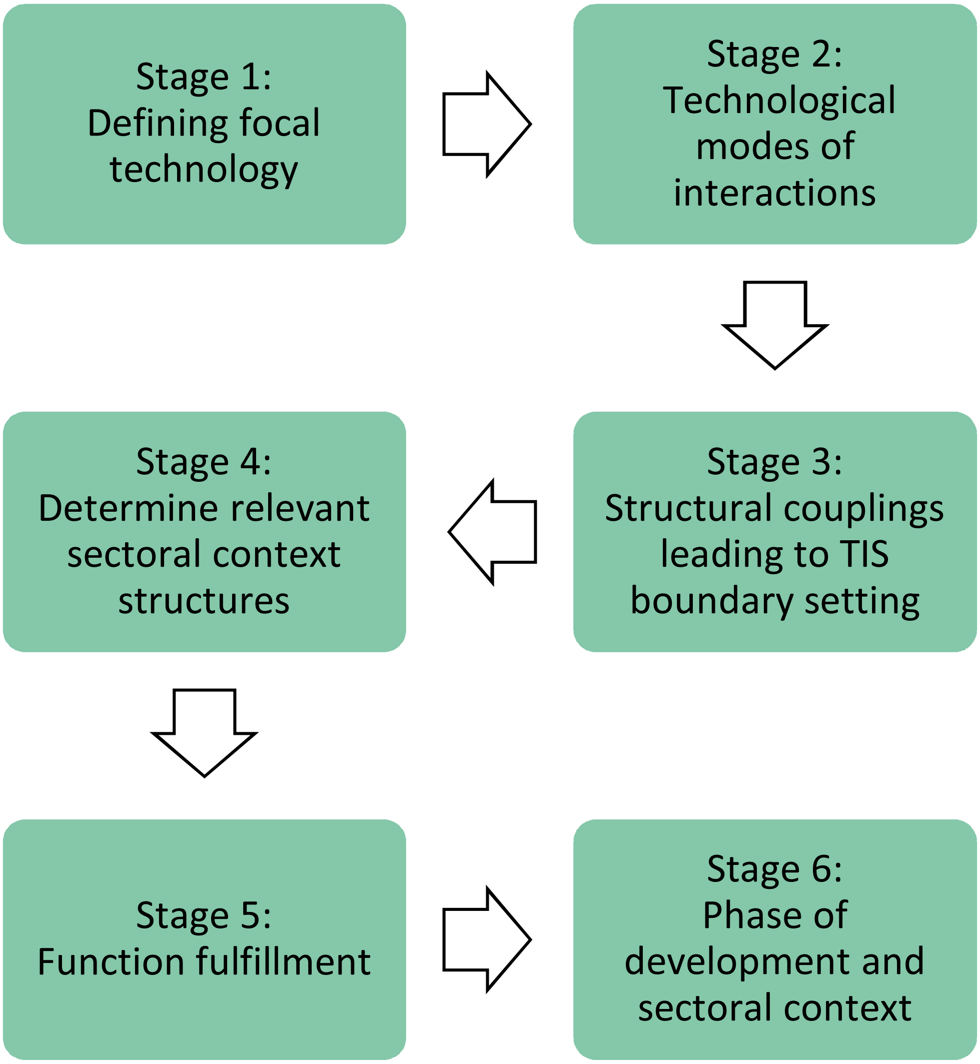

Fig. 1. TIS-analysis stages incorporating relevant contextual structures.

analyze all TISs separate from each other or to combine them. For instance, two strongly structurally coupled TISs may warrant analyzing them as a single system. In the fourth stage, relevant aspects of the sectoral context that influence the TISs as discerned in the previous stage were identified and the influence of these contextual structures on TIS development was analyzed. The fifth stage subsequently consisted of describing function fulfillment and inhibiting systemic problems in accordance with the functions as distinguished by Hekkert et al. [10]. Due to space constraints, the influence of the sectoral context on function fulfillment was thereby specifically stressed. Consequently, the results present the main problems pertaining to the internal structure of the heat pump TISs. The complete version of the analysis can be found in Kieft et al. [18]. Finally, as sixth and final stage, the phase of development of both TISs and the role of sectoral structures on TIS functioning were determined.

Data sources were collected between 2012 and 2017. For the first four stages, data were collected by a review of government documents and research reports, complemented by a number of semi-structured interviews, and internet websites that were used to get background information about specific initiatives in relation to heat pumps or to renovation more generally. Data for the fifth stage (function fulfillment and problem identification) was based on in-depth interviews with a wide variety of actors. These included government officials, housing associations, house renovation consultants, energy cooperatives, installers, heat pump manufacturers, and industry associations. In total, sixteen in-depth interviews were conducted, which lasted two hours on average (the set-up of the in-depth interviews is included in the Appendix). After transcribing these interviews in text, textual fragments mentioning systemic problems were coded using the procedure of open coding [29]. The resulting codes were subsequently grouped into higher-level categories, which resembled the process of focused coding [6]. The higher-level categories of codes are the systemic problems presented in this paper. Finally, the resulting systemic problems, were linked to the seven functions of innovation systems [10].

Results

This section is structured according to the six analysis stages as discerned in the previous section.

Stage 1: Defining focal technology in the Dutch context

Although there is a wide variety of heat pumps available, only a few types are fit for large scale implementation in existing Dutch houses.

In the Netherlands, by far most houses are heated using a high-efficient natural gas boiler Almost every house in the Netherlands thus has a connection to the gas grid, which can be explained by the large domestic natural gas reserves, discovered in the 1950s. The use of oil for central heating in combination with electricity for hot water – which is a common combination in other European countries – has never been prominent in the Netherlands. Electric heat pumps are seen as an improvement compared to the high-efficient gas boiler because of their high efficiency. The energy (in the form of heat) that is transferred to the house can be up to four times higher than the energy (in the form of electricity) necessary to run the pump.[4] If the electricity mix for running the heat pump is low-carbon or carbon-free, this adds to the benefits of the heat pump. What is more, because in the Netherlands houses are generally heated using hot water as medium (water as heat sink), only heat pumps that transfer heat to water are considered a viable large-scale option. This thus leaves out heat pumps that heat air. To conclude, conditions in the Netherlands are most favorable for the implementation of electric heat pumps using water as heat sink.

Within the category of electric heat pumps using water as heat sink, a distinction can be made between two main types. The first type – which will be called the *standalone heat pump* – has sufficient capacity for heating a house and providing hot water throughout the year. Only on very cold days and with high peaks in the use of hot water, additional back-up heating is necessary (generally based on electric resistance heating). The second type – the *hybrid heat pump* – has a lower capacity, making it on itself unable to heat a house throughout the year. It is called a hybrid, because this smaller capacity heat pump is generally used in combination with a gas-fired boiler (often, but not necessarily, integrated in a single machine). In theory, a hybrid heat pump can also be used in combination with an electric boiler. However, this is not a viable combination for the Netherlands, first because of the prominence of the gas-fired boiler, and second because of resistance from the electricity grid companies (because this combination leads to high peak demand on the electricity grid). The rest of the paper thus makes the distinction between the standalone heat pump as replacement for a high-efficient gas boiler, and the hybrid heat pump as addition to the high-efficient gas boiler.

Heat pumps can in theory make use of a wide variety of external heat sources (air, water, soil), but not all of these are viable options for larger scale implementation of heat pumps in existing houses. First, since many houses are not located nearby surface water, the use of water as heat source does not allow for large scale implementation. Second, although using soil as heat source has multiple advantages, for instance that the soil can also be used in the summer to store surplus heat and cool the house (air-conditioning), it is generally more difficult to install, especially for existing houses. For instance, there is a minimum distance between pits, which complicates installing multiple ground-based heat pumps in densely populated areas. This type of heat pump thus falls outside of the system boundaries. Since air is available for all houses air-based heat pumps allow for large-scale implementation. Some houses (especially newer houses) have an active ventilation system and thus have access to relatively hot ventilation air, which is a good heat source for the heat pump. Using ventilation air as heat source is only viable for hybrid heat pumps because the amount of useful heat in ventilation air is limited and insufficient to heat a house. Both standalone and hybrid heat pumps can make use of outside air. As only a part of the Dutch housing stock has an active ventilation system, for many houses using outside air as heat source is the most viable option.

Stage 2: Technological modes of interactions

Ideal conditions for a heat pump arise when the heat source has a relatively high temperature, a house is insulated well, utilizes a low-temperature heating system, and electricity from solar panels is available (e.g. [5]). A hybrid heat pump that uses relatively warm ventilation air as heat source thus generally has a higher efficiency compared to systems that use a lower temperature heat source. On the heat sink side, there are more possibilities for improving the conditions for the heat pump. First, the user sets requirements on the concurrent amount of heat required, for instance whether showering and doing the dishes should be possible at the same time, or at what speed a room can be heated up. Second, when a house is insulated well, the demand for heat is not only much lower, but also more constant. Insulation thus improves the conditions for installing a heat pump. Third, the required temperature of the heat sink matters. Floor heating or wall heating systems generally require lower temperature water. Such low-temperature heating systems thus also improve the conditions for using a heat pump. Finally, the availability of energy carrier matters. For instance, if a house already has solar panels on the roof, this availability of electricity may benefit the use of a heat pump. The above shows that, in addition to the high-efficient gas boiler, the hybrid heat pump, and the standalone heat pump, three additional technologies should be taken into account: (1) insulation technology, (2) low-temperature heating systems, (3) and solar panels.

On the level of direct physical technology interactions[5], a high-efficient gas boiler is hardly benefitted or inhibited by insulation, low-temperature heating systems or solar panels. Although water may need to be heated less often or toward a lower temperature after adding insulation or installing a low-temperature heating system, the high-efficient gas boiler remains a fitting technological choice for heating the water. Since a high-efficient gas boiler uses a negligible amount of electricity and this is generally available from the electricity network, installing solar panels also does not benefit or inhibit the high-efficient gas boiler. The high-efficient gas boiler is largely independent from other technologies, signaling *neutralism* relationships.

Insulation, low-temperature heating, and solar panels have the same interactions with hybrid heat pumps and with standalone heat pumps. First of all, heat pumps and insulation have a *commensalism* relationship, namely, insulation will lead to a more constant heat demand and thus improve the conditions for heat pumps. Installing a heat pump however, does not influence the case for insulation (which is always beneficial). Although heat pumps can make use of the electricity generated from solar panels, solar panels cannot make use of the heat generated by a heat pump, signaling another *commensalism* relationship. Finally, since the efficiency of a heat pump depends on the temperature raise necessary (efficiency is higher with lower temperature difference), a heat pump thus benefits greatly from a low-temperature heating system. However, a low-temperature heating system does not necessarily benefit from using a heat pump as the water can just as well be heated with a high-efficient gas boiler: a *commensalism* relationship.

Interactions between the standalone heat pump, the hybrid heat pump, and the high-efficient gas boiler are a combination of *competition* and *commensalism* relationships. The standalone heat pump is in *competition* with the high-efficient gas boiler as they are mutually exclusive means to provide space heating. The standalone heat pump is also in *competition* with the hybrid heat pump; only one or the other will

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[4] The performance of a heat pump is denoted with the so-called COP value (coefficient of performance). For instance, a heat pump with a COP of 3 can transfer three times more energy to the house than what is necessary to run the pump. A COP of 3 thus reflects an “efficiency” of 300%, although one should note that a heat pump does not convert energy but only transfers it.

[5] Next to direct physical interactions, there are also indirect and non-technological interactions. For instance, after installing both insulation and a low-temperature heating system, the high-efficient gas boiler may have overcapacity. When the high-efficient gas boiler is replaced, a lower capacity high-efficient gas boiler may then be chosen for. In addition, although a heat pump will run just as well on electricity from the electricity network as on electricity from solar panels, the latter may be cheaper on the longer run. Furthermore, competing technologies (e.g. hybrid and standalone heat pumps) may benefit from each other in terms of legitimacy; if the legitimacy of one is high, the others’ may be positively affected. To not unnecessarily overcomplicate matters, the main text is restricted to direct physical interactions.

be installed. Contrasting this, the hybrid heat pump has a *commensalism* relationship with the high-efficient gas boiler: a hybrid heat pump only works in combination with a high-efficient gas boiler, whereas a high-efficient gas boiler also works independently. Thus, the high-efficient gas boiler and the hybrid heat pump are – as technologies – tightly linked, whereas the standalone heat pump stands apart. Table 1 provides an overview of the main modes of interaction mentioned in this section.

Stage 3: Structural couplings

This section makes the move from the technologies themselves to the innovation systems that have formed around them. It is not only discussed to what extent a separate TIS has formed around respectively the standalone heat pump and the hybrid heat pump, but also to what extent these systems are structurally coupled, not only with each other, but also with the TIS of the high-efficient gas boiler. We do not strive for completeness in the description of these systems because the intention is limited to deciding whether to distinguish between two or three TISs in the rest of the analysis. For describing the system structure, three types of organizations with an especially prominent role are focused on, namely (1) manufacturers that develop and produce the technologies, (2) industry associations that represent the interests of actors in these systems, and (3) installers that install the technologies.

Manufacturers of standalone heat pumps are mostly foreign companies that sell their products in the Netherlands. By far most of these manufacturers do not produce hybrid heat pumps and/or high-efficient gas boilers. The standalone heat pump is installed by specialized installers that generally do not also install hybrid heat pumps or high-efficient gas boilers. In this way, the manufacturers and installers of standalone heat pumps are unique to the standalone heat pump TIS. This does not mean that the standalone heat pump TIS and the hybrid heat pump TIS do not show any structural overlap. For instance, there is a Dutch industry association for heat pump manufacturers (Dutch Heat Pump Association) that represents both standalone and hybrid heat pump manufacturers which set the goal of installing 300.000 additional heat pumps, independent of type, in the Netherlands before 2020 [32]. In addition, subsidy programs also do not distinguish between these two heat pump types. The trade association for heat pumps, the set goals, and available subsidies all represent structural couplings between the standalone heat pump TIS and the hybrid heat pumps TIS.

Actors in relation to the hybrid heat pump and the high-efficient gas boiler can hardly be discussed separate from each other since manufacturers of hybrid heat pumps are mostly Dutch manufacturers who originally produced, and still produce, high-efficient gas boilers. There are also manufacturers that only produce high-efficient gas boilers. What is more, few, if any, installers only install hybrid heat pumps. Instead, hybrid heat pumps are mostly installed by more advanced installers of high-efficient gas boilers that offer the hybrid heat pump as additional product. The average installer can only install a high-efficient gas boiler, although more installers have started to send their staff to training programs for also installing hybrid heat pumps. Clearly, these actors (manufacturers and installers) represent strong structural couplings between the hybrid heat pump TIS and the high-efficient gas boiler TIS.

Table 1
Main modes of interaction between relevant technologies (direct physical interactions).

Technology 1		Technology 2	Main mode of interaction
High-efficient gas boiler	vs	Low-temperature heating	Neutralism
High-efficient gas boiler	vs	Insulation	Neutralism
High-efficient gas boiler	vs	Solar panels	Neutralism
Heat pump	vs	Low-temperature heating	Commensalism
Heat pump	vs	Insulation	Commensalism
Heat pump	vs	Solar panels	Commensalism
Hybrid heat pump	vs	High-efficient gas boiler	Commensalism
Standalone heat pump	vs	High-efficient gas boiler	Competition
Standalone heat pump	vs	Hybrid heat pump	Competition

The TISs of insulation, low temperature heating, and solar panels stand largely apart from the heat pump and high-efficient gas boiler TISs. Manufacturers of insulation, low temperature heating and solar panels generally specialize in producing one technology. The installation is generally done by specialized companies. Structural couplings between the heat pump TISs and the TISs of the other technologies are rare, and are thus not further analyzed.

Fig. 2 provides an overview of the three TISs and shows what actors and institutions form structural couplings between them. Three things can be noted. First, the hybrid heat pump TIS does not have any unique actors or institutions: they are all shared with the other TISs. Second, the standalone heat pump TIS does have unique actors. Third, there are strong structural couplings between – on the one hand – the hybrid heat pump TIS and the high-efficient gas boiler TIS (shared manufacturers and installers), and – on the other hand – between the standalone heat pump TIS and the hybrid heat pump TIS (industry association, goals and subsidies). Clearly, the TIS of the standalone heat pump is much more independent compared to the TIS of the hybrid heat pump.

Although the above implies that analyzing the standalone heat pump TIS as separate entity makes sense, it also raises the question whether the hybrid heat pump TIS should be analyzed on itself or in combination with the high-efficient gas boiler TIS. Before being decisive on this matter, it is necessary to discuss relevant dynamics at sectoral level to which we turn next.

Stage 4: Relevant sectoral context structures

This section discusses different renovation goals that Dutch sectoral actors commonly strive for, and illustrates why, depending on the set goal, either a standalone heat pump, a hybrid heat pump or a high-efficient gas boiler will be preferred.

In the Netherlands, it was and still is quite common to set the renovation goal in relation to the energy label of the house. An energy label runs from label G (very inefficient) to label A++ (energy neutral). Each measure taken, which can be either an energy efficiency measure (e.g. insulation) or an energy production measure (e.g. solar panels), represents a certain increase of the energy label and, depending on the ambition level of the renovation, different technologies will be 'stacked'. The time-period between 2012 and 2018 was characterized by housing associations striving for the collective goal of reaching an average of label B in 2020, which was formalized in the Dutch energy covenant in 2013 (in Dutch: Energieakkoord).[6] As a result of this sector wide goal, many housing associations chose to renovate all of their houses to label B. However, there are also many housing associations that pursued label A or higher, sometimes due to intrinsic motivation, but often because the sectoral goal was set at reaching label B *on average.* By renovating part of their houses to label A or higher, housing associations could be less ambitious for the rest of their housing stock. In other words, both renovating toward label B and renovating to label A or higher were (and remain) common renovation goals.

Next to setting the goal in terms of energy label improvement, it is also common to renovate toward the goal of zero-on-the-meter. A zero-on-the meter house annually produces enough energy to offset the energy-use of an average family. This goal was introduced by the Dutch

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[6] The Climate Agreement (in Dutch: Klimaatakoord; https://www.klimaatakkoord.nl/), presented in 2019, succeeds the Energieakkoord (https://www.ser.nl/nl/thema/energie-en-duurzaamheid/energieakkoord).

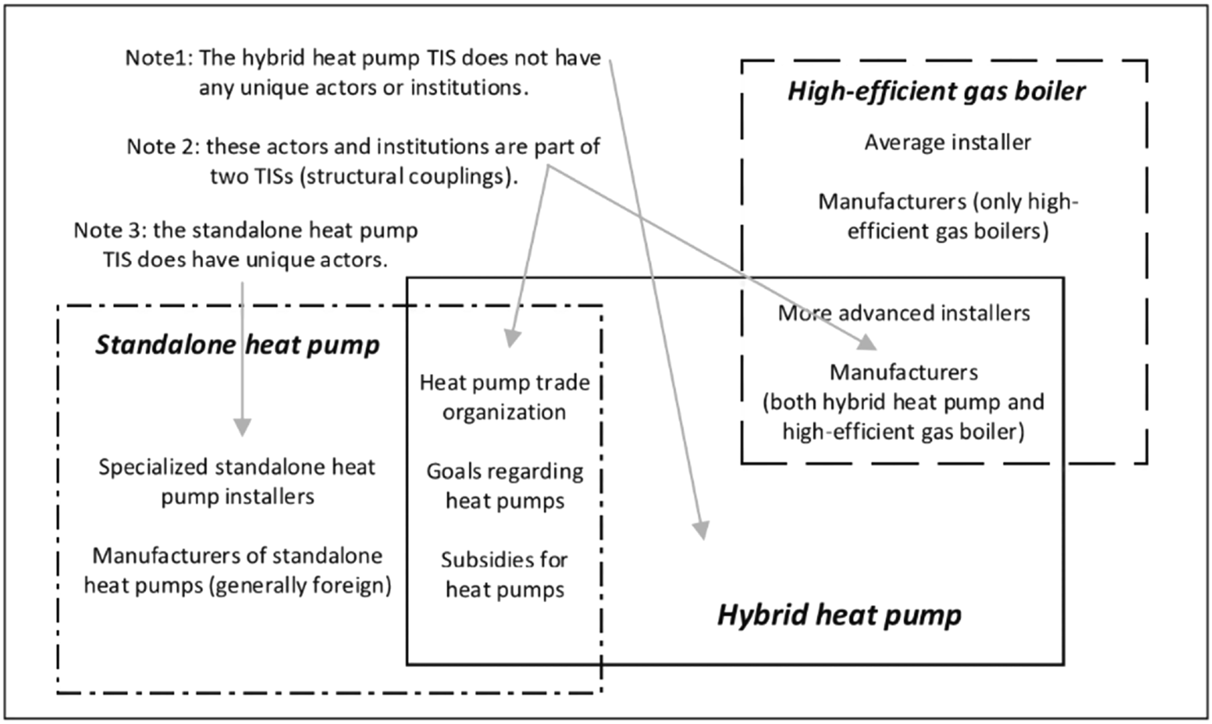

Fig. 2. Structural couplings between TISs.

government as part of the so-called "Energiesprong" program[7] between 2010 and 2016. In addition to the zero-on-the-meter goal, this program also advocated the use of so-called renovation concepts, which is a standardized methodology for renovating a particular type of house (e.g. a particular type of row house or flat building). By far most renovation concepts are geared to reaching zero-on-the-meter. Instead of performing renovation activities on site (which is common for label renovations), construction components are prefabricated in a factory after which the house is stripped and the prefab components are installed in a matter of days. What is more, most renovation concepts are all-electric, which means that the house is no longer connected to the gas grid after renovation. When the goal of zero-on-the-meter is thus set, measures are not 'stacked' as with energy label renovations, but form a coherent set of measures. In this way, renovations toward zero-on-the-meter differ substantially from energy label renovations.

What technologies can be used (and make sense using) strongly depends on the renovation goal pursued, and this is where it gets interesting for the heat pump. Label B can be achieved relatively easily with a bit of additional insulation, a high-efficient gas boiler and a couple of solar panels. A heat pump or low-temperature heating system are not necessary, but if used, they reduce the requirements for insulation and solar panels. For reaching higher energy labels it becomes increasingly harder: it requires not only better insulation and more solar panels, but usually also low-temperature heating and either a hybrid or a standalone heat pump. However, since the standalone heat pump is the more expensive of the two, the hybrid heat pump remains the obvious choice even for more ambitious energy label renovations. In other words, renovation goals of label A or higher are very difficult, if not impossible, to reach with a high-efficient gas boiler. For renovations toward zero-on-the-meter, especially when all-electric is strived for, the options are even more limited. Next to thick insulation, installing as many solar panels as possible, and using low-temperature heating, a hybrid heat pump is an absolute necessity. If all-electric is the goal, the only remaining option is a standalone heat pump. Table 2 provides an overview of the relation between renovations goals and technologies.

Table 2
Possibilities of using technologies for different renovation goals.

	Up to label B	Label A or higher	Zero-on-the-meter
Insulation	+	++	+++
Heat sink temperature	High temperature	Medium temperature	Low-temperature
Solar panels	A couple	Many	As many as possible
High-efficient gas boiler	Possible	Sometimes possible, but usually not	Impossible
Standalone heat pump	Possible, but expensive	Possible, but expensive	Usually necessary
Hybrid heat pump	Possible but not always necessary	Possible and usually necessary	Very difficult or impossible (in case of all-electric)

From the above we can also deduct that the conditions for using a heat pump improve with more ambitious renovation goals. This is a result of the technology/technology interactions as earlier explained in "Stage 2: Technological modes of interactions". Since insulation, low-temperature heating, and solar panels all have *commensalism* interactions with the heat pump, the more insulation, low-temperature heating and solar panels are used, the better the conditions for the heat pump become. Instead, since the high-efficient gas boiler has *neutralism* interactions with these technologies, the case for the high-efficient boiler does not improve with higher ambition levels. If ambitious goals are set (either label A or higher or zero-on the-meter), it is even necessary to install a heat pump since such goals cannot be reached with a high-efficient gas boiler.

In relation to the standalone heat pump, the discussion of structural couplings between TISs ("Stage 3: Structural couplings") already implied that its TIS is rather isolated from other TISs. This is confirmed further by the above discussion of renovation goals at sectoral level. The standalone heat pump is necessary for reaching zero-on-the-meter, but not an obvious choice for energy label improvements. What is more, the part of the sectoral system that facilitates zero-on-the-meter is strongly

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[7] https://energiesprong.org/.

dependent on further development of the standalone heat pump, and in turn, the TIS is strongly dependent on the success of this part of the sectoral system, making them strongly structurally coupled. Thus, when analyzing the standalone heat pump TIS, it is crucial to take the part of the sectoral context into account that facilitates zero-on-the-meter renovations.

In relation to the hybrid heat pump, the discussion of structural couplings between TISs ("Stage 3: Structural couplings") already implied that the TISs of the hybrid heat pump and the high-efficient gas boiler are closely connected. Also this insight is confirmed by the discussion on renovation goals. To reach higher energy labels, a combination of a high-efficient gas boiler and a hybrid heat pump becomes a necessity. In other words, not only from a technology perspective but also from a sectoral context perspective, it is difficult to separate between the hybrid heat pump and the high-efficient gas boiler. For this reason, the hybrid heat pump and high-efficient gas boiler will be considered a single TIS. What is more, this hybrid heat pump/high-efficient gas boiler TIS is very dependent on the part of the sectoral context that is striving for energy label renovations. At the same time, this part of the sectoral context is very dependent on this TIS, again reflecting strong structural couplings. Thus, when analyzing the hybrid heat pump/high-efficient gas boiler TIS, it is crucial to take the part of the sectoral context into account that facilitates energy label renovations. For linguistic purposes, this TIS will be called the hybrid/gas boiler TIS from here on.

Fig. 3 gives an overview of how the TISs of the standalone heat pump and the TIS of the hybrid heat pump/ gas boiler overlap with the sectoral context. Four things are noted: (1) the standalone heat pump and the hybrid/gas boiler TISs show structural overlap, (2) the two TISs are in competition for renovations of label A or higher, (3) actors in the hybrid/gas boiler TIS question the necessity for all-electric solutions within zero-on-the-meter renovations, which were prominent in early zero-on-the-meter renovations, and (4) a focus on all-electric solutions within zero-on-the-meter renovations gives the standalone heat pump free reign within zero-on-the-meter renovations. Clearly, the competition between energy label renovations against zero-on-the-meter renovations happening at sectoral level is of significant influence on the relative success of both TISs.

The function fulfillment for both TISs is presented in the upcoming section, during which the influence of sectoral context on function fulfillment is specifically stressed. In line with Fig. 3, for the standalone heat pump TIS, the influence of the sectoral context that is pursuing zero-on-the-meter renovations is emphasized, whereas for the hybrid/gas boiler TIS, the influence of the sectoral context that is pursuing energy label renovations is emphasized.

Stage 5a: Function fulfillment for the hybrid/gas boiler TIS

To start with, the numerous hybrid heat pumps sold between 2012 and 2018 indicate that most *entrepreneurial activities (F1)* have finished. Hybrid heat pump manufacturers have reached the end of the pilot stage and are planning for large scale implementation of their technologies. There were no main problems in this TIS that pertain to entrepreneurial activities.

In relation to *knowledge development (F2)*, even though the market for house renovations is a relatively new market for heat pumps (especially air-source heat pumps), heat pump technology has for long been used in other application fields. Therefore, further knowledge development in relation to heat pump technology in general, and thus also for the hybrid heat pump, revolves around minor performance increases. Within the analyzed time-period, knowledge development focused on integrating heat pump technology with other technologies prominently used for renovation, for instance on how badly installed insulation influences the efficiency of a heat pump. However, the segmented nature of the installation sector inhibited, and still inhibits, this type of knowledge development. Since most installers are highly specialized, it is difficult for them to view the technology they are specialized in as part of a larger whole. In this way, a problem at sectoral level is inhibiting further knowledge development within the hybrid/gas boiler TIS.

Knowledge regarding hybrid heat pump technology does not reach all relevant stakeholders, signaling weak *knowledge diffusion (F3)*. Although educating installers on heat pump technology is a high priority

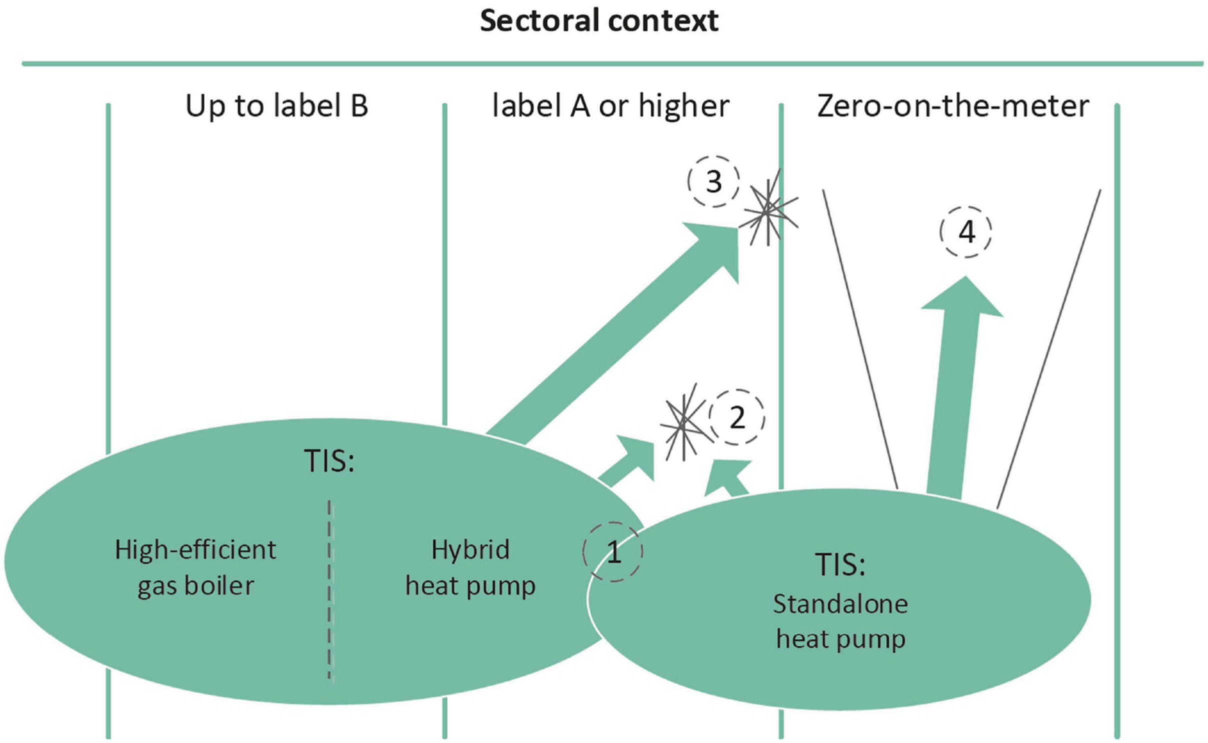

Fig. 3. Overlap between sectoral context and respectively, the standalone heat pump TIS and the hybrid/gas boiler TIS (see text for reference to the numbers 1–4).

for both industry associations and the government, this has only seen slow progress. The problem does not lie in the availability of specialized trainings for heat pump technology, but rather, it is not easy to persuade installers to take these trainings. Main reasons for this are lack of financial means or lack of time because of often busy schedules. In addition, the highly-specialized nature of installers means that there is little interest in learning about new technologies, and on how to integrate different technologies into a holistic approach. Again, actor distribution and characteristics at sectoral level are negatively influencing this function. Another problem relating to the sectoral context that was relevant during the analyzed time period (2012–2018) was that, although the energy label provides homeowners with a list of possible measures to take based on the characteristics of their house, it did not offer the option of a hybrid heat pump.[8] A problem pertaining to the TIS-itself relates to the multitude of terms that remain in circulation for describing the same type of heat pumps. This has the consequence that a rather high knowledge level is required to understand the information that is provided. For the bigger housing associations, this lack of clear information is mainly annoying since, as professional organizations, they often have the capacity to understand the available material. However, for homeowners that do not have such a knowledge base, the use of confusing terminology is highly problematic.

Guidance of the search (F4) in relation to the hybrid heat pump was during the time-period analyzed also highly influenced by the sectoral context, both in a negative and positive manner. For instance, the 2013 Dutch Energy Covenant contained concrete renovation goals for housing associations and the private rented sector. Unfortunately, although this has given a boost to taking energy-efficiency measures in general, the set ambition level was too low to be highly beneficial for the hybrid heat pump. Namely, the goals were specified as reaching label B on average, which can also be attained with only a high-efficient gas boiler (see Table 2). What was highly beneficial for the hybrid heat pump, were discussions about sustainable heat that are taking place in the context of the TIS, of which sustainable heat subsidy programs that include heat pumps was the result. In this way, the sectoral context played, and still plays, an important role in the extent to which actors are guided toward the use of the heat pump.

As *market formation (F5)* in relation to especially housing associations was stimulated by the goals set in the Dutch Energy Covenant, especially the market for homeowners has remained small. Having an indicative energy label[9] was made obligatory when selling a house, thereby stimulating the new owners to consider taking energy-efficiency measures. However, that the hybrid heat pump was not mentioned on the energy label as possible measure certainly did not stimulate its uptake. Another problem is that installers are hesitant to provide performance guarantees for the hybrid heat pump since its performance depends so much on technologies installed by other companies. This is unfortunate, since it makes especially homeowners hesitant to invest.

As already mentioned, especially smaller installers struggle with *mobilizing sufficient resources (F6)*, both in terms of finances and time. In addition, the height of initial investment costs is a leading criterion for homeowners, which does not benefit the hybrid heat pump as it comes in addition to a high-efficient gas boiler. What is more, as result of the relatively high electricity tax compared to the gas tax in the Netherlands, the payback time of a heat pump remains long, if the investment pays back at all.[10] Although the heat pump is energetically quite efficient, this is not always the case in financial terms.

Finally, in relation to the function *creation of legitimacy (F7)*, proponents of the standalone heat pump and the hybrid heat pump bring each other' technology in discredit to such an extent, that it negatively affects the legitimacy of heat pump technology in general. In addition, since many installers are highly-specialized and are used to install high-efficient gas boilers only, they refrain from advising the use of a hybrid heat pump.

Fig. 4 provides an overview of what main problems inhibited function fulfillment in the hybrid/gas boiler TIS between 2012 and 2018. Although some problems are endogenous to the TIS, most problems relate to the sectoral context. Problems are one of three types. First, problems that relate to the energy label, namely that the hybrid heat pump was not mentioned on it and that many actors renovated not higher than label B. Second, problems that relate to installers. They are highly-specialized, often in installing gas boilers only, and they are usually smaller companies with a lack of financial means and time to follow trainings about the hybrid heat pump. In addition, they remain hesitant to provide performance guarantees, because of the interdependencies between the heat pump and other technologies utilized. Finally, the relatively high electricity tax can be considered a problem at the level of the electricity sector. In all, it can be concluded that the sectoral context had, and still has, a major influence on the functioning of this TIS.

Stage 5b: Function fulfillment for the standalone heat pump TIS

As the use of concepts was already prominent in the market for new houses, *knowledge development* in relation to renovation concepts that strive for the zero-on-the-meter goal already had a sound knowledge base to work from. Still necessary knowledge development thus related to measuring the actual performance of the heat pump within a renovation concept. Between 2012 and 2018, the focus of knowledge development shifted from the drawing board to pilot projects.

That standalone heat pumps are already available on the market, signals that *entrepreneurial activities (F1)* at technology level has also largely finished. Pilot projects still underway between 2012 and 2018 focused on how to integrate standalone heat pumps in zero-on-the meter renovations. During this period, within the rental houses covenant (“Stroomversnelling Huur”),[11] the focus moved from pilot projects on individual houses to pilot projects on complete blocks of houses. Within the covenant that focusses on homeowners (“Stroomversnelling Koop”), first pilots were also initiated. Unfortunately, the diverse range of wishes from homeowners proved too difficult to overcome, ultimately leading to the cancellation of this covenant in 2016. Since it is the designated choice for zero-on-the-meter renovations (see Table 2), this was bad news for the standalone heat pump.

Knowledge development (F2) mainly focused on the performance of the heat pump in the renovation concepts.

Knowledge diffusion (F3) between participants was an important pillar in both renovation concept covenants (“Stroomversnelling”). It was furthermore made sure that knowledge already developed in the covenant for rental houses, which started earlier, was diffused to the more recent covenant for homeowners. Although multiple heat pump manufacturers participated in zero-on-the-meter pilot projects, they remained hesitant to share the gained knowledge among each other. The lack of knowledge sharing between heat pump manufacturers was a main systemic problem during this time period.

The zero-on-the-meter goal created a shared target to work toward (*guidance of the search, F4)*. In addition, both covenants were strictly

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[8] The energy label methodology has been adapted in the meantime and now includes the hybrid heat pump.

[9] An indicative energy label is a preliminary indication of the energy label based on a paper-based analysis. For instance, instead of visiting a house, an energy label issuer calculates the energy label based on bills for taken energy-efficiency (e.g. insulation) and/or energy-production measures (e.g. solar panels).

[10] Tax on gas was increased substantially, and tax on electricity reduced, in 2020. However, in terms of energy content, electricity remains taxed higher.

[11] https://stroomversnelling.nl/.

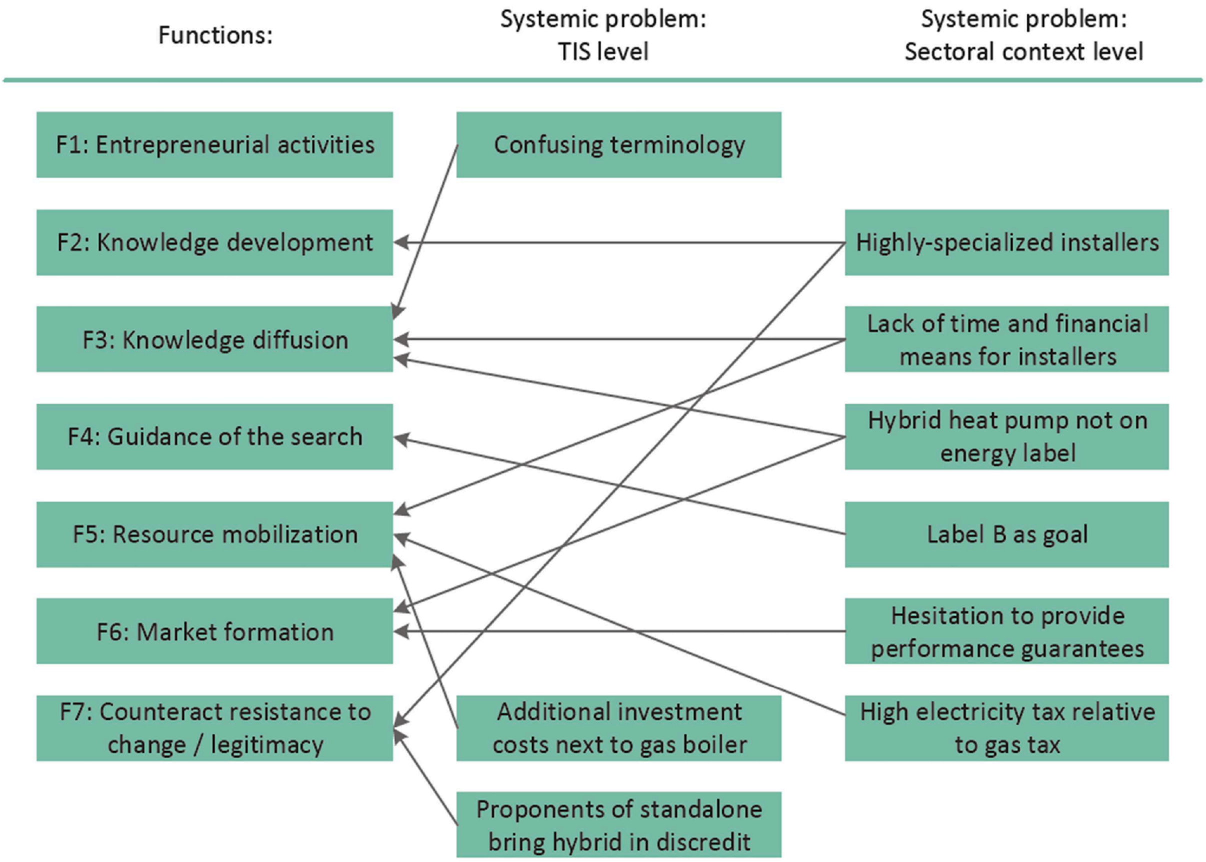

Fig. 4. Main problems inhibiting function fulfillment in the hybrid/gas boiler TIS between 2012 and 2018.

organized with the purpose of not creating unnecessary delays. For instance, participants officially had to commit to actively participate, and new actors were not allowed after the start-date if there was any reason to believe that this would create delays. However, despite that all-electric became the norm for achieving the zero-on-the-meter goal in the covenant for rental houses (thus requiring the use of a standalone heat pump), the necessity of all-electric remained heavily debated in the covenant for homeowners. The argument was that the zero-on-the-meter goal can also be achieved with gas-based technologies, which in practice means the application of a hybrid heat pump. The debate around gas-based or all-electric undermined the application of standalone heat pumps and was a main systemic problem hindering the function of *guidance of the search*.

In relation to *market formation (F5)*, both renovation concept covenants already tried to create a market for renovation concepts even though they were not yet available. For instance, to participate in the covenant for rental houses housing associations had to commit to implement the still to be developed renovation concepts, which created a strong the incentive for concept developers. In addition, even though renovation concepts for homeowners were not yet available, the "Energiesprong" program initiated a national television show in which homeowners were introduced to the idea, and a website on which homeowners could already express their interest was launched. What is more, to participate in the covenant for homeowners, actors (e.g. provinces, municipalities, energy cooperatives) had to commit to actively promote renovation concepts under their residents/members. The main systemic problem in relation to market formation in this period was that only a small portion of actors in the Netherlands had signed the covenants.

In relation to *resource mobilization (F6)*, especially for financial resources, activities were initiated to facilitate both covenant participants and clients (homeowners and housing associations). To start with, the "Energiesprong" program assisted participants in both covenants with knowledge and limited financial means. Furthermore, since the concept developers in especially the covenant for rental houses were relatively large, financial resources could be freed up relatively easy. Although concept developers for the homeowner market are generally smaller companies, they often work together to share in development costs. To facilitate clients to mobilize funds for a renovation to zero-on-the-meter, activities were focused on letting the appraisal value of the house increase significantly after the renovation. In addition, the national government initiated higher mortgage loans for homeowners, and lower landlord fees for housing associations, if they choose for a zero-on-the-meter renovation. Since a renovation to zero-on-the-meter remained more expensive than the set goal of 45.000 euro, subsidies remained necessary for the pilot projects. Although small subsidies were available for homeowners that participated in zero-on-the-meter pilot projects, these were too low to make participation cost-effective. The still high costs of zero-on-the-meter renovations was a main systemic problem that was inhibiting resource mobilization between 2012 and 2018.

The fact that the heat pump is the designated choice for a zero-on-the-meter renovation (see Table 2) contributes to the *creation of legitimacy (F7)* for this technology. Between 2012 and 2018 the debate mainly revolved around what type of heat pump to install (either standalone or hybrid), a debate related to the question to strive for all-electric or to remain using gas (see *guidance of the search*). In other words, although at the sectoral level there is substantial resistance against the zero-on-the-meter goal, there is little resistance against the use of a standalone heat pump when this goal is strived for. That proponents of the standalone and the hybrid heat pump were bringing each other's technology in discredit did hamper the legitimacy of heat pump technology in general.

Fig. 5 provides an overview of main problems inhibiting function fulfillment of the standalone heat pump TIS between 2012 and 2019.

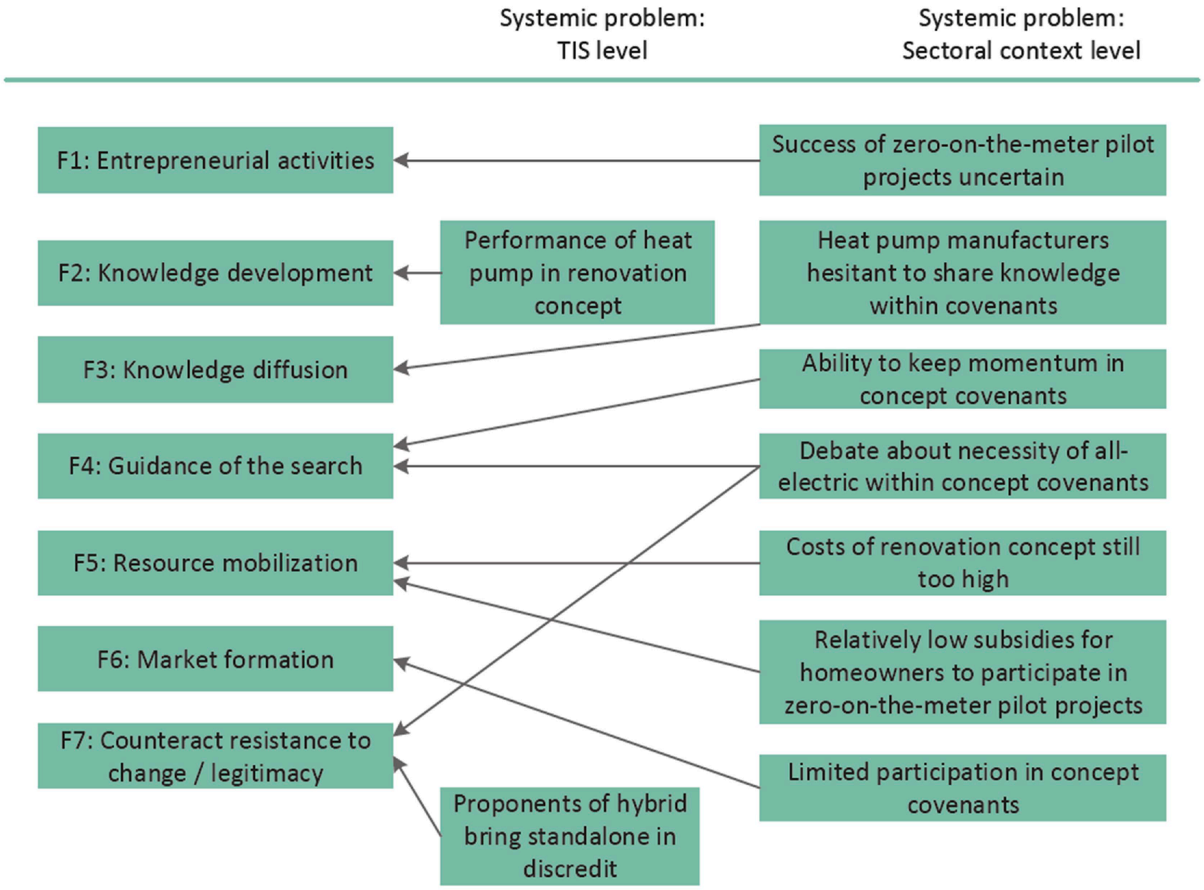

Fig. 5. Main problems inhibiting function fulfillment in the standalone heat pump TIS between 2012 and 2018.

The table again shows that by far most systemic problems relate to the sectoral context. The standalone heat pump TIS is not only highly dependent on the success of the zero-on-the-meter goal at sectoral level, preferably with a strong focus on all-electric, but was also dependent on the success of the two renovation concept covenants (“Stroomversnelling”). Together with the findings for the hybrid/ gas boiler TIS, it may be concluded that the sectoral context had much influence on the functioning of these Technological Innovation Systems.

Stage 6: Phase of development and sectoral context structures

The quite different function fulfillment for the innovation systems of the hybrid/gas boiler TIS, and of the standalone heat pump TIS, shows that they resided in a different phase of development between 2012 and 2018. Which phase of development can be determined by comparing the function fulfillment for both systems to what theory expects for a certain phase of development (see Theory section).

Between 2012 and 2018, the hybrid/gas boiler TIS reached the end of the *take-off* phase, but still had difficulties moving to the *acceleration* phase. Although the hybrid heat pump proved itself in pilot projects (F1), it remained confronted with resistance (F7) from installers who are used to installing high-efficient gas boilers. This lack of legitimacy made installers reluctant to provide performance guarantees, which in turn inhibited the creation of a market (F5) which is the most important function for moving to the acceleration phase. The incomplete information on the indicative energy label also did not help for creating a market. In all, the hybrid/ gas boiler TIS has difficulties moving to the *acceleration* phase, whereby by far most barriers reside not within the TIS itself but relate to label step renovations (see “Stage 5a: Function fulfillment for the hybrid/gas boiler TIS”).

Although the standalone heat pump TIS still resided partly in the *development* phase between 2012 and 2018 (pilot projects were still in full swing), activities were also initiated to reach the *take-off* phase and beyond. As also explained in “Stage 5b: Function fulfillment for the standalone heat pump TIS”, even before pilot projects were finished, much effort was already put in forming a market (F5). In other words, activities were already initiated to support the system in reaching the *acceleration* phase. Although these activities have proven successful in the market for social housing, they were not successful in the homeowner market. Within the social housing market, pilot projects on individual houses ended and pilot projects focusing on renovating complete housing blocks started. Within the homeowner market, pilot projects were initiated but the homeowner covenant was ultimately abandoned due to difficulties of developing tailor-made renovation concepts for individual houses and homeowners with individual wishes. Despite encouraging activities within the heat pump TIS itself, the analysis made clear that the success of the heat pump depends mainly on whether zero-on-the-meter renovations become a success (see “Stage 5b: Function fulfillment for the standalone heat pump TIS”). Only then will the standalone heat pump be able to reach the *take-off* phase.

Reflecting on the above, it becomes clear that the relative success of both TISs, and thereby the success of hybrid and standalone heat pumps, is highly influenced by how developments within the sectoral context unfold. Progress in implementing hybrid heat pumps has been slow, for a large extent because of systemic problems relating to the more traditional energy label steps renovations. This part of the sectoral context, the part that is advocating renovations based on energy label steps, has proven itself to indeed be conservative and ‘quite stable’, just as literature expects. However, the standalone heat pump was found to be significantly favored by the emerging of zero-on-the-meter renovations at sectoral level. That an autonomous change in the sectoral context may positively influence the development of a Technological Innovation

System is theoretically nothing less than striking.

Discussion

This discussion reflects on theoretical and methodological lessons that can be drawn from the presented case study. The following subjects are considered: (1) the importance of understanding the technology in focus and its modes of interaction with other TISs, (2) the importance of taking sufficient context into account, (3) the kind of effect contextual structures have on TIS development and (4) the consequences of limiting this investigation to the period between 2012 and 2018.

Firstly, giving attention to heat pump technology itself and to its modes of interaction with other technologies proved to be imperative. Without it, the distinction between the hybrid and standalone heat pump would not have been made, and the hybrid heat pump would not have been analyzed together with the high-efficient gas boiler. This would not only have complicated data collection (since actors commonly mean one type or the other when talking about the 'heat pump'), but also have obscured the quite significant differences between the two in terms of system structure, function fulfillment, systemic problems, and phase of development. Bergek et al. [2] were indeed right when stating that analysts should strive for "a more than superficial grasp of technologies involved" (p. 61).

Secondly, the case confirms the importance of taking sufficient contextual structures into account. Figs. 4 and 5 made evident that most systemic problems inhibiting the respective TISs of the hybrid/gas boiler TIS and the standalone heat pump are not endogenous to the TIS, but rather relate to the sectoral context. An analysis of 'only' the heat pump TIS would have clearly come to quite different conclusions. The presented case study shows that taking context explicitly into account during a TIS-analysis requires additional activities compared to what is explained by TIS-literature, especially in the earlier analysis stages (see "Method").

Thirdly, the presented case study also provides new insights into the role of the sectoral context on TIS development. Namely, so far, literature has described the role of the sectoral context as follows: "A sector […] provides a quite stable context, which individual TISs either have to adapt to or try to change to their own benefit" [2]. However, the presented case study shows that, although part of the sectoral context of the heat pump TISs is indeed static, some parts are also highly dynamic. The more traditional renovation approach based on energy labels indeed provides a quite stable context for the hybrid/ gas boiler TIS. However, the advent of the zero-on-the-meter goal is a case in point of a not only autonomous, but also highly significant change in the sectoral context that is affecting both heat pump TISs. Actors in the standalone heat pump TIS clearly benefit from zero-on-the-meter renovations, even though in initiating it they had no role. In other words, what is true for any type of contextual structures is also true for sectors: "They tend to change over time, both as a matter of autonomous developments in context structures and as a consequence of the focal TIS growing and becoming more mature" [2].

Fourthly, as also mentioned in the introduction, this investigation deliberately focused on the relative stable policy period between 2012 and 2018 because the central research question – What inhibited the implementation of heat pumps in the Netherlands between 2012 and 2018 and what was the influence of the sectoral context? – cannot unambiguously be determined in a fast-changing policy environment. Although the Climate Agreement signed in 2019 will lead to changes in the policy context in coming years, the exact content of these changes remain largely unclear. An important change is the growing attention for the role of district heating in the heat transition. This does not only involve the decarbonization of existing district heating networks, but also the shift from individual heating (gas boilers) to district heating, mainly in neighborhoods dominated by social housing. This implies that the TISs of stand-alone heat pumps and the hybrid heat pump/high efficient boiler now also face competition from the DH TIS. For the long term the possibility of large scale diffusion of renewable gas (hydrogen from electrolysis, or bio-based) cannot be excluded. However, these options will not play a big role in the heat transition before 2030, other than that the promise of renewable gas (offering the possibility of a relative smooth heat transition given the dense gas infrastructure in the Netherlands) plays at least a role in local discussions about the best alternative for natural gas. Where information used in this paper has been overtaken by time (e.g. the change in both the taxing of electricity and gas), this has been highlighted. The theoretical insights on the role of sectoral structures and the methodological insights into how to incorporate contextual structures within a TIS analysis are independent of the time period investigated.

Concluding remarks

The relative success of the hybrid heat pump versus the standalone heat pump was found to be highly dependent on how the competition between label step renovations versus zero-on-the-meter renovations unfolds at sectoral level. By far most identified barriers, both for the hybrid heat pump and the standalone heat pump, relate to the sectoral context and not to the relative TISs. This shows, without doubt, that the role of the sectoral context is highly significant and should sufficiently be taken into account during a TIS-analysis. The method used for the presented assessment may provide future researchers inspiration for how to do this. What the analysis also showed is that the influence of the sectoral context can be substantially different from what literature suggests. The analysis of hybrid heat pumps within label step renovations showed how sectoral context can indeed be 'quite stable' and hamper technological change, just as literature suggests. However, contrasting literature, the upcoming of zero-on-the-meter renovations is a case-in-point of an autonomous change in the sectoral context that significantly favors the standalone heat pump. When analyzing the influence of sectoral context on TIS-development, keeping an open mind is necessary.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Interview set-up

Explaining the scope of the research (5 min)

- Application of heat pumps in the existing housing stock.
- Introducing the TIS framework in laymen terms.

Step 1: Context interviewee (15 min)

1. Current position
2. Working / educational background
3. Most relevant target groups you work with:
   a. Social housing corporations
   b. Private home owners
   c. Home owner associations (apartment buildings)
   d. Private renters
4. Relevant experience in renovation projects

Step 2: Barriers for heat pump application: Identify barrier categories (10 min)

1. Choose target group (see step 1).
2. Which is the main barrier category for applying the heat pump? And the second? And the third? (cards are used for visualization)
3. Rank the barrier categories.

4. Are the pre-defined categories complete? If not, write this barrier category down on an empty card.
5. Briefly discuss why the lowest ranked barrier categories are considered less important.

Step 3: Specify barrier categories (20 min)

1. Start with the number 1 ranked barrier category.
2. Ask which specific barriers belong to this category and why these are relevant for the target group chosen. (label the barrier, write it down on an empty card and position it next to the barrier category)
3. Repeat this until the first five barrier categories are split up into barrier labels.
4. If relevant, go back to step 2 and choose the next target group.

Step 4: Coherence and cause/effect (15 min)

1. Trying to let the interviewee make a connection between the barriers: which of the barriers are fundamental, which are symptoms of other barriers in place?

Step 5: Solutions (15 min)

1. For each barrier (starting with the barriers in the main barrier category) answer the following questions:
   a. How to solve this barrier?
   b. Which stakeholders are crucial for solving this barrier and why?
   c. Which external conditions might be helpful for solving the barrier?

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