Master's Thesis – master Innovation Sciences

Utrecht University

Analyzing the Influence of Environmental and Sectoral Context Conditions on Technology Development and Diffusion:

A Comparative Case Study of Residential Heat Pumps in European Countries

Author: de Werdt, T (Thijs); +31 (0)6 460 618 69; t@dewerdt.nl
Supervisor: dr. Wesseling, J. H.
Date of submission: 15-1-2017
Utrecht University, Graduate School of Geosciences, Innovation Sciences

Summary

Although widely used for analyzing renewable energy technologies, critics argue that technological innovation systems are lacking in their incorporation of influences that lie outside system boundaries, here referred to as context conditions. Without sufficient recognition of these influences, a technological innovation system analysis is not capable of fully understanding why a certain technology's performance is at a certain level or why it has certain system dynamics. The present research aims to contribute by assessing the influence of environmental and sectoral context conditions on the performance of residential heat pumps in Europe for the period 2005-2014. Performance was segregated into two dependent variables, with technology diffusion being measured as heat pump installations and technology development as patents. Temperature and relative humidity, population density and urbanization are included as environmental context. Energy labels, installation sector firm size, electricity prices and electricity grid reliability are included as sectoral context. A mixed method approach has been applied in order to supply statistical results with exegeses from interviews and desk-research. Results suggest that the perceived positive effect on diffusion of increased HP efficiency with higher temperatures is overestimated since the quantitative results show a negative correlation between temperature and diffusion, likely due to a lower heating demand at higher temperatures. Relative humidity was found to have little to no effect on both diffusion and development. High levels of urbanization were found to be slightly more problematic for diffusion than high population densities, although developments such as noise reductions have allowed further diffusion in these areas in the last decades, to the point that the focus on developing noise reductions has now faded. The relationship between development and diffusion has been found to be inversely related in several other instances as well. In short, it is likely that further assessment of context conditions is bound to deliver a greater understanding of what drives technological innovation system performance.

Index

1. Introduction

The effect of CO_2 emissions on the earth's temperature has led to CO_2 emission reduction targets being instated (Kanemoto et al., 2014; Singh, Muetze, & Eames, 2010). To achieve the needed CO_2 emission reductions, sustainability transitions towards more efficient and sustainable technologies are required (Bergek et al., 2015; Kemp, 1994). These are particularly important in the residential sector, where buildings consume 16 to 50 percent of total energy inputs (Pombo, Rivela, & Neila, 2016; Saidur, Masjuki, & Jamaluddin, 2007; Vieira, Stewart, & Beal, 2015). For Europe, an average of 40 percent is reported (Balaras et al., 2000; European Parliament and Council, 2012). Appreciable improvements leading to CO_2 emission reductions are possible in this area (Balaras et al., 2000). Implementing high efficiency appliances such as heat pumps (HPs) is amongst these improvements. HPs with an average coefficient of performance (COP) of five (meaning 1 kWh of electricity is used for pumping 5 kWh of heat into the house) are available (Mayes, 2007; Singh et al., 2010; Tarnawski et al., 2009).

The European Standard EN14511 defines HPs as an: "encased assembly or assemblies designed as a unit to provide delivery of heat. It includes an electrically operated refrigeration system for heating. It can have means for cooling, circulating, cleaning and dehumidifying the air. The cooling is by means of reversing the refrigeration cycle" (Mayes, 2007, p.22). HPs offer opportunities for achieving heating (and cooling) efficiencies greatly exceeding 100 percent (Cho et al., 2016)**.** HPs can achieve this by using electricity to pump heat from a source, transfer the heat into a refrigerant, transport it, and deliver it at a destination. Multiple heat sources can be used, such as outside air, water and ventilation air.

However, diffusion of HPs is spatially very dissimilar (Heiskanen & Matschoss, 2016). Several factors influence the development and diffusion of HP variations differently (Heiskanen & Matschoss, 2016; Kieft, 2017). The technological innovation systems (TIS) framework is widely used in studies investigating how renewable energy technologies and their innovation system can be stimulated (Bergek et al., 2015; Hekkert et al., 2007; Markard, Raven, & Truffer, 2012). However, this perspective does not explain why the performance of the HP TIS is spatially this dissimilar. One TIS critique is that the framework does not pay enough attention to its contextual setting (Bergek et al., 2015). At the same time, many in the scientific community agree that the influence of context on a TIS is of the utmost importance in understanding sustainability transitions (e.g. Bergek et al., 2015; Kieft, 2017; Truffer & Coenen, 2012). For example, the high population density in the Netherlands (Bergek & Jacobsson, 2003) reduces the availability of surface area for ground-source HPs to supply residential heating requirements (Kieft, 2017). Also, the COP of HP's is directly related to temperature of the source from which heat is extracted (Guoyuan, Qinhu, & Yi, 2003; Ma & Chai, 2004). The higher the source temperature, the more efficient a HP can operate. Therefore, the availability of high temperature sources is likely to influence HP diffusion.

Some work has been done with respect to better integration of these kinds of context in a TIS analysis. Bergek et al. (2015) conceptualize a context structure (CS) template that includes technological, sectoral, political and geographical CSs, with each CS comprising several context conditions. However, the current conceptualization of geographical context focusing on local embeddedness and global networks is argued to be quite narrow. Especially for the case of HPs, a technology that exploits local temperature differences, general environmental context parameters such as outside air temperatures (Vieira, Stewart, & Beal, 2015), relative humidity (Yao et al., 2004) and population density (Kieft, 2017) are known to be of importance**.** This paper therefore proposes an environmental CS that includes these environmental parameters.

In Europe, according to the European Heat Pump Association (EHPA), three HP variants used for space heating are diffused more widely than others, namely air-water, ground-water and air-air HP's (EHPA, 2016). Country specific diffusion data for these variants is obtained from the EHPA for the period 2005-2014. The research therefore focusses on this period. In general, a TIS can also influence CSs; in such cases the TIS is said to be structurally coupled with this CS (Bergek et al., 2015). For the environmental CS, this is argued to be unlikely since this CS is not easily influenced by a single technology, looking at difficulties associated with combatting climate change.

Across European countries, environmental context conditions such as population density vary with location (the World Bank, 2015a). By conducting a comparative case study on countries within Europe, these differences in environmental context pave the way for a valuable research avenue, as the effect of varying environmental context on TIS performance can be observed. By looking at HP related patent applications and diffusion numbers combined with environmental data by country, overall TIS performance in the sense of technological development and diffusion (Carlsson & Stankiewicz, 1991), but also the direction of diffusion (e.g. faster diffusion of ground-water HPs) can be observed, allowing for a large amount of countries to be incorporated. Patents can only be used as an indication for the overall technological development of HPs (not the specific direction), since patents are often formulated in a general sense, not attributable to one HP variant.

For the Netherlands, Kieft (2017) identified the sectoral CS as an important CS to include, since the renovation, installation and electricity sectors would influence TIS performance to such an extent that the obtained data is polluted too much if these influences are not accounted for. This could also be true in other countries, which is why the sectoral CS is included. Interviews are held and desk research is performed to cross-validate the obtained results. The following research question is synthesized:

How did environmental and sectoral context conditions influence the development and diffusion of the residential HP technology over the period 2005-2014 across European countries?

By answering the research question, the scientific community gains further insight into how context conditions are influencing HP technology performance. Since the constituents of technological performance, development and diffusion, are two key processes of a TIS (Carlsson & Stankiewicz, 1991), the understanding of how the HP TIS is influenced by environmental and sectoral context conditions is increased as well. This can help transition studies to better integrate the impact of these influences, allowing for a better understanding of why certain technologies are performing differently across countries. This helps to negate the criticism that TIS theory is lacking a much needed incorporation of contextual influences.

The research aims to provide a better understanding of HPs and what drives their innovation systems. The findings can be used by policy makers to account for spatial differences with regard to environmental and sectoral context conditions when giving policy recommendations. If, for example, outside air temperature is not sufficient for achieving high efficiencies with air-source HPs in a certain countries, the inclusion of this context condition allows for detecting that this is not the result of a dysfunctional innovation system, but that the cause for low performance actually lies in unfavorable environmental context. In a similar fashion, the findings can be helpful to academics when doing scientific research, and to the private sector, when assessing HP market potential in a certain area. This way, it is better possible to determine where HPs are viable and where not. As a result, HPs are applied in areas for which they are well suited, reducing CO_2 emissions.

Next, Chapter 2 describes the theoretical framework employed in answering the research question, together with relating hypotheses and the conceptual model. Chapter 3 delineates HPs. Chapter 4 describes the argumentation for different methodological choices that are made, together with the operationalization table. Chapter 5 presents the results. Chapter 6 discusses the results together with placing them in a broader context, making suggestions for future research avenues and giving policy recommendations, after which Chapter 7 concludes.

2. Theory

This Chapter describes the scientific theory employed in the research, starting with elaborating on the TIS in Section 2.1. Section 2.2 describes the context structures in five consecutive subsections, together with presenting the hypotheses for the sectoral (Section 2.2.4) and environmental (Section 2.2.5) context structures. Section 2.3 provides a visual representation of the theoretical framework in a conceptual model.

2.1 Technological Innovation Systems

Often employed in sustainability transition studies are innovation systems. An innovation system is defined as "all institutions and economic structures that affect both rate and direction of technological change in society" (Hekkert et al., 2007, p. 415). It includes different kinds of structural components that together perform a set of system functions. Different innovation systems exist that focus on different scales of analysis, including innovation systems at the national, regional, sectoral and technological level. These are respectively called national systems of innovation (NSI), regional innovation systems (RISs) sectoral innovation systems (SISs) and TISs. The CS template to which this thesis adds (see Bergek et al., 2015) builds on the TIS framework. Although this thesis focusses on the CSs of the TIS framework, a short introduction to the TIS framework is presented first.

2.1.1 Structural Components

Three structural components, namely actors, networks and institutions (and sometimes tech/materiality), are included in the TIS framework. In short, every relevant actor, network or institution is included. However, setting the definition of 'relevance' to broad can cause information overload for the analyst(s). In order to keep the analysis feasible, only those structural components that engage in or influence key innovation processes should be included. These key innovation processes are called system functions (see Section 2.1.2; Hekkert et al., 2007), and together form the functional pattern of an innovation system. Relevant actors include, for example, firms in the complete value chain, universities and other research organizations, public entities, interest organizations such as industry associations or non-governmental organizations (NGOs), venture capitalists, financial organizations and standard-setting organizations. Relevant networks include those whose mission is to solve a certain TIS related problem, diffuse TIS related knowledge, or perform a different TIS related task. Examples are formal networks such as public-private partnerships and standardization networks, or informal networks such as communities. Both formal and informal rules are included as institutions (Hekkert et al., 2007). Examples are culture, norms, laws, regulations and routines. It is important to keep a broad perspective on institutions as, for example, higher level (EU) regulation or 'unwritten rules' could be important as well. It is also noted that a lack of structural components can tell analysts something. For example, the TIS could then be in an early, formative phase.

2.1.2 System Functions

Because system functions represent key innovation processes, they are another important element of a TIS analysis (Bergek et al., 2008; Hekkert et al., 2007). Hekkert et al. describe seven functions including entrepreneurial activities, knowledge development, knowledge diffusion through networks, guidance of the search, market formation, resource mobilization and the creation of legitimacy. It should be noted that these functions are not performed in isolation. Different actors, networks and institution perform or frustrate different functions, and the functions influence each other dynamically. The focus in the present research lies on TIS performance. This can be regarded to as the primary outcome of the key innovation processes or system functions. In other words: "a technological system may be described as a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology" (Carlsson & Stankiewicz, 1991, p.94). Two aspects of technology performance, diffusion and development, are hypothesized to be similarly influenced by context conditions since greater diffusion indicates a larger market size, allowing for greater developmental capital availability. This is likely to results in a greater amount of submitted patents. Similarly, development is likely to lead to more diffusion (Wesseling, Faber, & Hekkert, 2014).

2.2 Context Structures

The more recently developed CS template by Bergek et al. (2015) can be described as a synthesis of former work on TIS context. The template includes technological, sectoral, political and geographical context structures (Bergek et al., 2015). The majority of former works have each focused on only one context structure in isolation (e.g. technological context). Bergek et al. combining the previous works in a template does not imply that all CSs have to be included in every analysis (Kieft, 2017). For the case of heat pumps, at least for the Netherlands, Kieft has shown that especially the technological (TIS) and sectoral (SIS) CSs are of importance. Furthermore, Bergek et al. (2015) add the concepts of external links and structural couplings. These are forms of interaction that can occur between a TIS and context structures.

The difference between these two forms of interaction lies in the degree of interdependence (Bergek et al., 2015). Where external links indicate that a TIS is influenced by a certain CS, structural couplings emerge only when a TIS can influence that same CS as well. However, in practice, this distinction is not always easily made. For example, influences such as energy prices are a reasonably clear-cut external link for newly introduced technologies with a large energy consumption/production that have not attained widespread diffusion yet, as their overall energy consumption/production is still relatively low. However if a technology with high electricity demand goes mainstream in a country or even internationally, this could very well have an influence on the scarcity, and thus the price of electricity (Hirth, 2013).

2.2.1 Technological Context

Bergek et al. (2015) describe the technological CS as "…'other' TISs that interact in different ways with the focal TIS" (Bergek et al., 2015, p.55). Interactions can be of a competitive or supportive nature (Bergek et al., 2015; Sandén & Hillman, 2011). When a TIS offers complementary resources for the focal TIS, they are related in a supportive way. When a TIS competes with the focal TIS for market share, interaction is competitive. Interaction with other TISs happens vertically as well as horizontally (Bergek et al., 2015). Vertically related TISs can, for example, provide raw materials, components and services needed by the focal TIS. Innovations in one TIS can therefore require innovations in up- and downstream TISs (related to the innovation ecosystem framework; Adner, 2006). Horizontal interaction especially happens when TISs require the same inputs and assets, or when TISs have similar outputs (Bergek et al., 2015). Especially with the latter, interaction is often of a competitive and external nature. However, even in competitive settings, alliances can be formed in order to, for example, collectively fight the regime (Bergek et al., 2015; Suurs & Hekkert, 2009; Ulmanen, 2013). These alliances, such as organized lobbying practices, can be described as structural couplings as well. Horizontal structural couplings also emerge through institutions that, for example, promote a broad range of renewables.

2.2.2 Sectoral Context

Sectoral interaction with a TIS has been long acknowledged in the literature (Bergek et al., 2015; Geels, 2004; Johnson & Jacobsson, 2001; Kemp, 1994; Malerba, 2002; Smith & Raven, 2012). Sectors are defined "in terms of the production, distribution and use of technologies and products needed to serve a certain function for prospective users" (Bergek et al., 2015, p.56). It is important to note that a TIS often interacts with multiple sectors (Bergek et al., 2015). Wesseling & Van der Vooren (2016) argue this is the case due to two reasons. First, both systems can be defined by products or technologies. Second, system delineations for both TISs and SISs are flexible. Boundaries are often set depending on the research question. This implies that delineation is much needed for an analyst in order to reduce clutter. Kieft (2017) argues "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" (Kieft, 2017, p.68). Therefore this thesis only focusses on the sectoral CS together with the main addition of this research, the environmental CS. Other CSs are shortly explained, but no hypotheses are formulated.

Kieft (2017) identifies the renovation, installation and electricity sector to be of importance for the HP TIS the Netherlands. First, the renovation sector is identified as important due to problems with legitimacy of the Dutch system using energy labels. Since these energy labels were instigated due to EU regulation (Teffer, 2015), it is suspected that this problem could be more wide-spread. This leads to hypothesis 1:

1. The current implementation of house energy labels frustrates the development and diffusion of HPs.

Second, small firms with a lack of financial means and time to investigate the possibilities of HPs are identified as being problematic in the Dutch installation sector (Kieft, 2017). Although installation firms are part of the HP TIS itself, the fragmented nature of installation firms is a broader sectoral characteristic instead of technology specific. Therefore Kieft attributes it to the sectoral context in the Netherlands. It is assumed that this is no different for the rest of Europe. This leads to hypothesis 2:

2. Small firms in the installation sector frustrate the development and diffusion of HPs.

Third, a high electricity price after taxes is found to be problematic for HPs in the Dutch electricity sector (Kieft, 2017). When consumers have to pay a relatively high price for electricity, HPs have to be more efficient to still achieve the same cost savings compared to alternatives such as heating with natural gas, petroleum products or by utilizing a district heating network. High electricity prices can increase HP cost savings when traditional electrical heating elements were first used for space heating, but since electricity only makes up about 12 percent of the energy input for space heating in the EU27 (Connolly et al., 2014), compared to 44 percent natural gas, 17 percent petroleum and 13 percent from district heating, on average, this is less often the case. This seems to indicate that an inverse relationship between electricity prices and HP development and diffusion exists, leading to hypothesis 3:

3. The price of electricity after taxes is inversely related to HP development and diffusion.

Furthermore, HPs depend on the supply of electricity to generate heat. The preferred energy source for end-users is increasingly becoming electricity (Pesola & Hirvonen, 2017). Especially in countries where other energy sources such as gas have been used for space heating in the past, higher peak loads on the electricity grid can be observed when heat demand is high. This implies that when the electricity grid is not reliable enough in the sense that it is able to handle high peak loads and limit outages, this could hamper HP diffusion. This leads to hypothesis 4:

4. Electricity grid reliability is positively related to HP development and diffusion.

2.2.3 Political Context

While a TIS already incorporates policy through institutions, the compatibility of a TIS with its political CS on multiple levels (region-level, nation-level, international-level, etc.) is not included in the original framework (Bergek et al., 2015). The political CS can be described as political ideologies or beliefs that can influence the legitimacy of a focal TIS positively or negatively (Bergek et al., 2015). Through this TIS function (legitimation), the political CS influences the entry or exit of new, resource adding actors into the TIS. The political CS also influences the availability of public financial resources by influencing public resource allocation.

2.2.4 Geographical Context

Research shows our current economies are becoming more internationalized (Carlsson, 2006). While the TIS framework originally was designed as a global system, the majority of TIS applications use national delineations (Bergek et al, 2015). This can cause researchers to miss out on important insights. However, even with internationalization, Patel argues that "…what happens in home countries is still very important in the creation of global technological advantage for firms" (Patel, 1995, p.212). One possible middle ground between these views can be found in a TIS analysis that focuses on one or multiple nations, while including other important interactions in the geographical CS (Bergek & Jacobsson, 2003).

2.2.5 Environmental Context

Environmental parameters are not included explicitly in either the CS template, a traditional TIS analysis or the geographical CS. Bergek et al. (2015) mention 'natural conditions' once, but do not specify the concept further. It is here argued that many technologies that are put forward in sustainability transitions rely heavily on these environmental parameters. Examples are wind turbines that rely on the availability of wind (Ackermann, 2005), PV panels that depend on solar irradiation (Šúri, Huld, & Dunlop, 2005) and HPs that utilize environmental heat (Vieira, Stewart, & Beal, 2015). Therefore, this thesis argues that the influence of the environmental CS is crucial to the success of these technologies and for explaining geographical patterns of TIS performance. In the following, specific context conditions that are deemed important are specified.

Since HPs are more efficient with higher temperatures, average annual outside air temperatures (simply called temperatures from here on) are especially of importance for HP variants that utilize heat from outside air (Vieira, Stewart, & Beal, 2015). When temperatures are more sufficient for high efficiencies, the need to drill expensive boreholes for ground-source HPs is reduced but the overall viability of HPs increases, since efficiencies similar to that of ground source HPs can be achieved with lower initial capital injections when temperatures are sufficient for air-source HPs. This leads to hypotheses 5 and 6:

5. A higher temperature stimulates the development and diffusion of HPs.
6. A higher temperature stimulates the development and diffusion of air-source HPs and frustrates the development and diffusion of ground-source HP development and diffusion.

Average annual outside air relative humidity (relative humidity from here on) determines the rate of ice buildup at temperatures near zero degree Celsius on outside air units (Yao et al., 2004). The more water is in the air, the faster unwanted ice will settle, that needs to be defrosted. This reduces the energy efficiency of outside air HPs, increasing the incentive to drill boreholes for ground-source HPs. This leads to hypotheses 7 and 8.

7. A higher relative humidity frustrates the development and diffusion of HPs.
8. A higher relative humidity stimulates the development and diffusion of ground-source HPs and frustrates the development and diffusion of air-source HP development and diffusion.

Finally, population densities are of importance for the availability of enough ground area for ground-source HPs to be installed (Kieft, 2017). Borehole drilling machinery requires space and boreholes need to be placed at a sufficient distance from each other in order to be able to extract enough energy from the ground(water). For air-source HP's, the problem of noise pollution is reported to be problematic when neighbors live close-by (Hewitt et al., 2011). This leads to hypothesis 9:

9. A higher population density frustrates the development and diffusion of HP's.

Related to this is the degree of urbanization in a certain country, since a high rate of urbanization implies that a large part of the population is living in close proximity to each other. This leads to hypothesis 10:

10. A higher degree of urbanization frustrates the development and diffusion of HP's.

2.3 Conceptual Model

Figure 1 shows a visual representation of a TIS together with the technological, sectoral, political, geographical and environmental CSs. The CSs overlap with the TIS itself and with each other, representing components that play a role in multiple CSs.

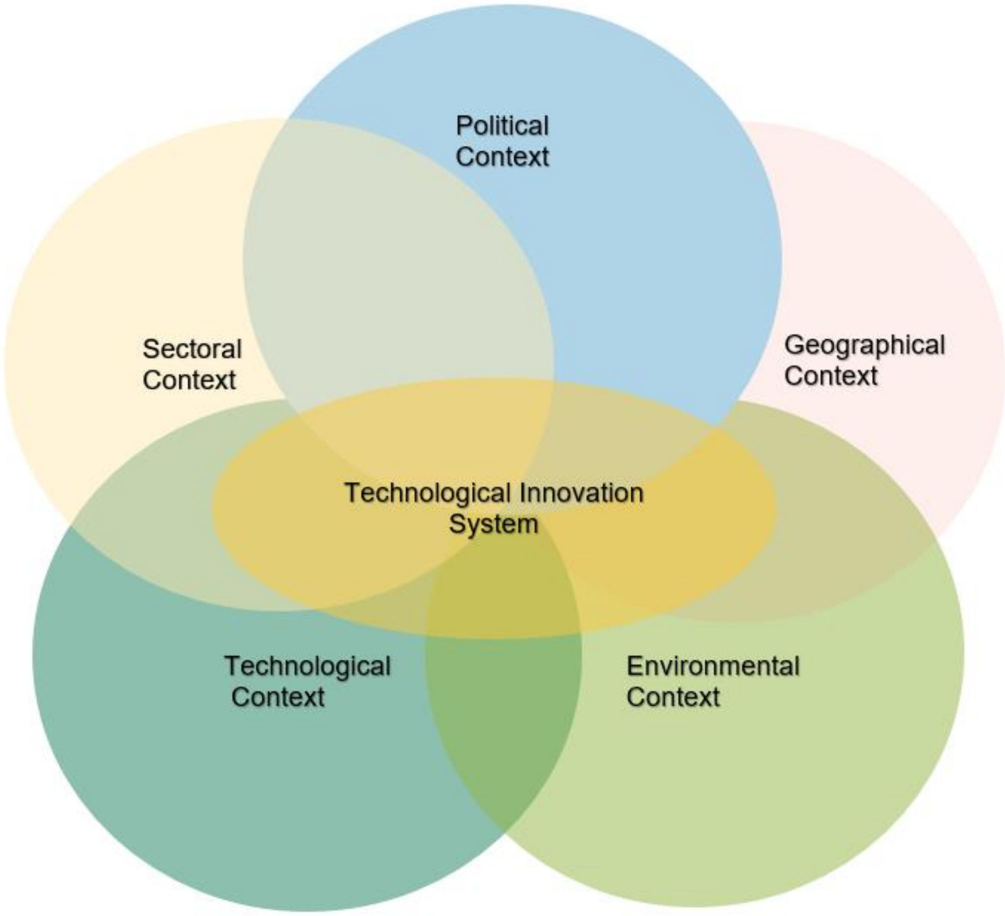

Figure 1: Conceptual model showing the focal TIS partly overlapping with all contextual structures identified by Bergek et al. (2015) and with the environmental CS added in this research. All context structures also show overlap with each other.

3. Technical Delineation of Focal Heat Pumps

As noted in the introduction of this research, the development of residential HPs across Europe is investigated in a comparative case study. This Chapter describes in further detail what the research includes as residential HPs.

Many different types of HP variants are available. A HP "…transfers heat from an external heat source to the inside…" (Kieft, 2017). This technology is found in a variety of applications ranging from refrigerators to closed vehicles. Here, the focus lies on HPs that are used for heating living-areas (space-heating), because of the energy intensity and thus the potential for energy use reduction when installing HPs with COPs far exceeding one. Even then, a wide range of HPs would be included in the research. Different types of residential HPs are available using different external sources and heat sinks (Kieft, 2017). In order to keep data input as low as possible, while securing the highest possible relevance of the research, only the HP variants with a large market share are included.

The EHPA (2016) distinguishes five different HPs. Only the HPs variants with substantial market shares (see Figure 2) are included because these are the most representative for the HP TIS. The 'exhaust air' HP uses the energy in pre-heated ventilation air that is on its way to be disposed of in the outside air. Due to its small market share, it is excluded from this research. A sanitary hot water HP does not heat living areas and is therefore excluded. The 'ground/water' HP uses the energy stored inside the upper layers of the earth's core as an external source. It is included because of its substantial market share. In this research, no distinction is made between open or closed loop and vertical or horizontal ground-source HPs as this would not be likely to create any additional insights with current indicators (see Section 3.1.1), and due to a lack of more specific data. The 'air/water' HP uses outside air as a source and delivers heat to a central heating circuit to heat living areas. Since it is used for space heating and has obtained a relatively large market share, it is included. The 'reversible air-air w/heating' HP uses the energy in outside air as an external source and delivers the heat directly to the inside air for space heating, and is included since it has the largest market share of all variants (see Figure 2).

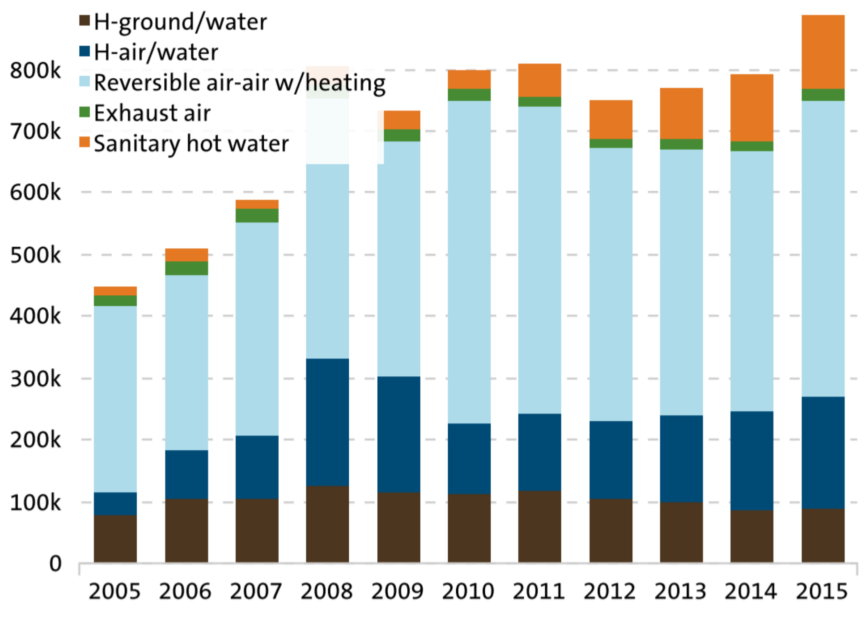

Figure 2. "Development of HP sales in Europe 2005-2015, by category" (EHPA, 2016).

4. Methods

4.1 Research Design

The contribution of this research lies in analyzing the impact of the environmental and sectoral CSs on residential HPs in Europe. Patent applications and diffusion numbers of the included residential HP variants are used as dependent indicators for analyzing TIS performance in terms of technology development and diffusion. The research investigates how dependent indicators are influenced by the environmental and sectoral CS indicators, as described in Table 1. A mixed methods approach is employed in conducting the research. Quantitative data is collected that enables performing a statistical analysis on the relation between dependent and independent variables. Qualitative data is collected in two ways. Interviews are held and desk research is performed to cross-validate the outcome of the statistical analysis and to identify possible other influences that could explain differing TIS performance in countries.

A comparative research design is chosen due to the explorative nature of the research (Bryman, 2012). When including a comparative element in the analysis, especially with social phenomena that are not well understood, a judgement can be more easily made as findings can be related to each other. This way, the influence of varying environmental CSs on TIS performance can be observed. It is important to note that no TIS analysis is done. Two overarching TIS processes or goals are analyzed, diffusion and development, in order to be able to broaden the scope of the research and to include a reasonable amount of countries. By doing so, the influence of context conditions will likely become more clear since a larger geographical area can be included, in which context conditions vary more than within countries. Also, this enables the research to conduct statistical analyses with countries as cases, what would not be possible with only a few countries. Table 1 describes the operationalization scheme for analyzing TIS performance and the environmental and sectoral CSs.

Table 1. Operationalization scheme. For corresponding interview questions, see Appendix A.

Concepts	**Indicators theoretical framework**	**Indicator type**	**Measurement**	**Literature source**	**Interview questions**
TIS performance	Development	Dependent	Amount of patents for HPs including all variants per million inhabitants	Haupt, Kloyer, & Lange, 2007; Pilkington & Dyerson, 2006; Wesseling, Faber, & Hekkert, 2014	N.a.
	Diffusion		Average yearly number of installations per million inhabitants by country for all included HP variants over the period 2005-2014	Wesseling, Faber, & Hekkert, 2014; Wesseling et al., 2015	N.a.

Environmental CS	Temperature	Independent	Average annual outside air temperatures in degrees Celsius	Vieira, Stewart, & Beal, 2015	3.a
	Relative humidity		Average percentage of annual outside air relative humidity in capital	Yao et al., 2004	3.b
	Population density		Average number of inhabitants per square mile	Hewitt et al., 2011; Kieft, 2017	3.c
	Degree of urbanization		Percentage of population living in cities	Hewitt et al., 2011; Kieft, 2017	3.d
Sectoral CS	Renovation sector	Independent	Implementation of house energy labels (qualitative)	Kieft et al., 2017	3.e, 4.a/b/c
	Installation sector		Installation firm size (qualitative)		3.f, 5.a/b
	Electricity sector		1. Average electricity costs after taxes 2. Reliability of electricity grid (qualitative)		3.g, 6.a/b

4.2 Data Collection

Five different data types are collected for conducting the analysis. Three are of a quantitative nature, and two are of a qualitative nature.

4.2.1 Quantitative Data

First, a non-publicly available dataset was obtained by contacting the EHPA. The dataset contains information on country specific HP diffusion figures for the three included HP variants in the period 2005-2014. Second, patent data is collected.

Patent applications and grants including all HP variants were counted for every country, since exploratory patent research indicated it is impossible to subdivide the vast majority of patent applications amongst specific HP variants. The vast majority of patent applications are defined rather broad as this increases their intellectual property value, which is one of the reasons for patenting (Sullivan, 1999). Patent searches are performed at the website “Espacenet”. One search is performed for each country. Countries gain a patent count if one of the inventors of the patent application was living in that country at the time of submission (searches were performed for the country codes of inventors). Other options would be to count patents based on the country codes of submission-, request- or priority numbers, but this is argued to be less representative of patent origins because these can all be applied for in other countries than the one that actually plays an active role in the inventing process. Searching for inventor country codes removes the problem of so-called patent families being counted in other countries, although a patent that is filed in multiple countries is still counted several times for the country in which the inventor is situated. Furthermore, searches were done with “heat pump” in the title or summary and F24D as cooperative patent classification. This class includes “domestic- or space-heating systems, e.g. central heating systems; domestic hot-water supply systems; elements or components therefor” (Espacenet, 2017). Including the “heat pump” keywords (with quotation marks) in the search ensures that no other heating systems from the same patent classification are included. Related keywords such as “reversible air conditioner” (without quotation marks) did not deliver any mentionable or relevant results and are therefore excluded. Finally, patents were not collected for a certain time frame, all available data is put to use.

Finally, data for several environmental variables was collected. These include electricity prices[1] (Eurostat, 2017), population densities (World Population Review, 2017), urbanization percentages (Central Intelligence Agency, 2017), temperature (Weatherbase, 2017) and relative humidity[2] (World Weather & Climate Information, 2017).

4.2.2 Qualitative Data

For obtaining qualitative data, the aim was to perform one semi-structured interview with a producer, distributor or HP association member in every included country. Semi-structured interviews are appropriate when the research area is explorative in nature (Bryman, 2012), which is especially the case with the environmental CS. Due to an exceptionally low response rate of 1,6 percent, interviews could not be held in every country. Therefore, 10 interviews were held by phone or Skype and 3 by email, all in different countries (see Table 2).

Table 2. Data collection by country

Country	Requests sent out	DATA INPUT
Austria	42	Desk research
Belgium	5	Interview producer
Switzerland	44	Desk research
Czech Repub.	30	Interview producer
Germany	295	Interview HP association
Denmark	14	Interview distributor
Estonia	2	Desk research
Spain	8	Desk research
Finland	88	Desk research
France	10	Desk research
Hungary	3	Email interview producer
Ireland	4	Email interview producer
Italy	80	Interview producer
Lithuania	18	Desk research
Netherlands	3	Interview producer
Norway	9	Interview HP association
Poland	3	Interview distributor
Portugal	13	Desk research

[1]: Annual consumption 2500kWh-5000kWh, including VAT, taxes and levies, CH value from different source: http://www.alpiq.com/media-target-group/dossiers/electricity-price.jsp, CHF exchange rate of 21 juli 2016 is used: .206 Swiss francs = .18919 Euro. Source: http://valutaomrekenen.co/206-chf-eur

[2] Data was read from a graph with monthly relative humidity percentages in the capital of every country. This data was averaged to obtain yearly averages. Relative humidity percentages in capitals were used since data was unavailable for nations. Capitals often house a significant part of the population

Sweden	12	Interview producer
Slovakia	90	Email interview HP association
United Kingdom	23	Interview HP association
Total	796	

For the countries in which interviews could not be conducted, desk research was performed in order to obtain results for these countries as well. Desk research was also performed in order to validate overall results. For choosing interviewees, producers were preferred since these are most likely to have a thorough awareness of different (environmental) influences on HP development and diffusion. Distributors only sell HPs, but work closely with the producers themselves, and are included. HP association members represent the interests of HP producers (and other actors in the value chain) and where therefore also considered adequate. In Table 3, the interviewee countries and desk research sources are presented with their corresponding numbers.

Table 3. Countries with corresponding source numbers and types

Country	Interview number	Country	Desk research source number	
Ireland	I1	**Austria**	Energy Innovation Austria, 2016	D4
Czech Republic	I2	**Switzerland**	Bundesamts für Energie, 2015	D5
Poland	I3	**Estonia**	Kuhi-Thalfeldt & Lahtvee, 2016	D6
Hungary	I4	**Spain**	Asociación de Fabricantes de Equipos de Climatización, 2017	D7
Norway	I5	**Finland**	Pesola & Hirvonen, 2017	D8
Netherlands	I6	**Finland**	Hirvonen, 2017	D9
Belgium	I7	**France**	Nille, 2015	D10
United Kingdom	I8	**Lithuania**	Gaigalis et al., 2016	D11
Sweden	I9	**Portugal**	Colaco, 2015	D12
Denmark	I10	**Multiple**	EHPA, 2013 Bettgenhäuser et al., 2013 Litina, 2016	D1 D2 D3
Slovakia	I11			
Italy	I12			
Germany	I13			

4.3 Data Preparation

The main output from quantitative data collection was an excel file with diffusion numbers by country and the amount of patent submission by country. The diffusion data from the EHPA was first averaged for yearly installations by country. This gave a more realistic number for diffusion numbers since some countries had more data gaps than others. The averaged data was then controlled for population sizes since population size is an unwanted influence that needs to be accounted for. The data was inspected with the software program SPSS in order to detect any outliers, non-normal distributions, heteroscedacity, non-linear bivariate relationships, multicollinearity and dependent errors (Ferrari, 2009; Field, 2013). These are all regression assumptions. This was done by looking at data summaries, correlations, boxplots, histograms and scatterplots. Furthermore, skew and kurtosis, Durbin Watson, multicollinearity and variance inflation factors values of the data are evaluated. When assumptions were violated, data is log-transformed and checked again after log-transformations. When the data still violates assumptions after transformation, data is ranked in order to be able to perform the non-parametric Spearman's Rho and Kendall's Tau tests

As for qualitative data, a set of audio files was collected from the interviews. After each interview, data was transcribed in software called NVIVO. In NVIVO, nodes were created for the indicators and other influences that comes forward. Interview transcripts statements are linked to nodes that are created in NVIVO**.** This prevents the researcher from drowning in statements by giving an overview of what interviewees agrees with what influences. Also, "positive", "negative" and "neutral" nodes were created to indicate whether a statement indicated a positive, negative or neutral influence on HP development and diffusion.

4.4 Data Analysis

The prepared quantitative data was analyzed in SPSS by fitting a linear multiple regression model for those cases that comply with regression assumptions (Ferrari, 2009; Field, 2013). From the fitted model, fitted values, residuals and regression coefficients were obtained. The relationships in focus were checked for significance and magnitude. When regression assumptions were violated even after data transformation, the non-parametric Spearman's Rho and Kendall's Tau tests were carried out on individual relationships. Results from the quantitative analysis were then compared to the nodes from NVIVO to confirm and provide insight into the statistical results.

4.5 Research Quality

Scientific research quality guidelines include 'internal validity', 'external validity' 'construct validity' and 'reliability' of the research (Bryman, 2012; Peter, 1981). Internal validity is improved by applying triangulation. Data is triangulated by using multiple, both quantitative and qualitative, sources for each indicator and country. External validity is limited since results cannot be generalized to other TISs due to the use of non-probability sampling. The sampling method can be called non-probability sampling since the cases (countries) were selected purposely without the inclusion of a random element, because data was only available for countries within Europe. While technically the results are not generalizable, results can be used as an indication for how similar renewable energy technologies are influenced by the environmental and sectoral context structures in other TISs and for how the HP TIS is influenced by context structures outside Europe. Construct validity is limited with regard to HP development since using patents as an indicator for development has its limitations (see Chapter 6). Reliability and more specifically replicability is improved by keeping an audit trail that includes interview transcripts and other notes. Furthermore, interview questions are disclosed in Appendix A and linked to indicators in the operationalization table (Table 1).

5. Results

This Chapter presents the results, starting with some overarching patterns of diffusion and development in Section 5.1. Section 5.2 present several results in tables, including descriptive statistics of the dataset (Table 4), qualitative results (Table 5) and quantitative (Table 6 & 7) results. Then the results on specific context conditions are presented in separate sections (Section 5.3-9). A summary of all results is presented in Section 5.10 by including a table with the combined results (Table 8). Since semi-structured interviews were conducted, interviewees have gotten the opportunity to elaborate on important influences that lie outside the current operationalization. These additional results are presented in Section 5.11.

5.1 Diffusion and Development

As an introductory overview of spatially dissimilar HP diffusion is shown in Figure 2, which shows the annual European heat production by HPs per capita in 2014 by country (EHPA, 2014; the World Bank, 2015b). Although in absolute numbers France has almost twice the heat production of that of Sweden (EHPA, 2014), Figure 2 shows that after controlling for inhabitants, France loses its lead position to Sweden and several others. Sweden is in the leading position with 1.31 TWh's of heat produced for every million inhabitants. It is followed by two other Scandinavian countries, Norway (.85 TWh) and Finland (.73 TWh).

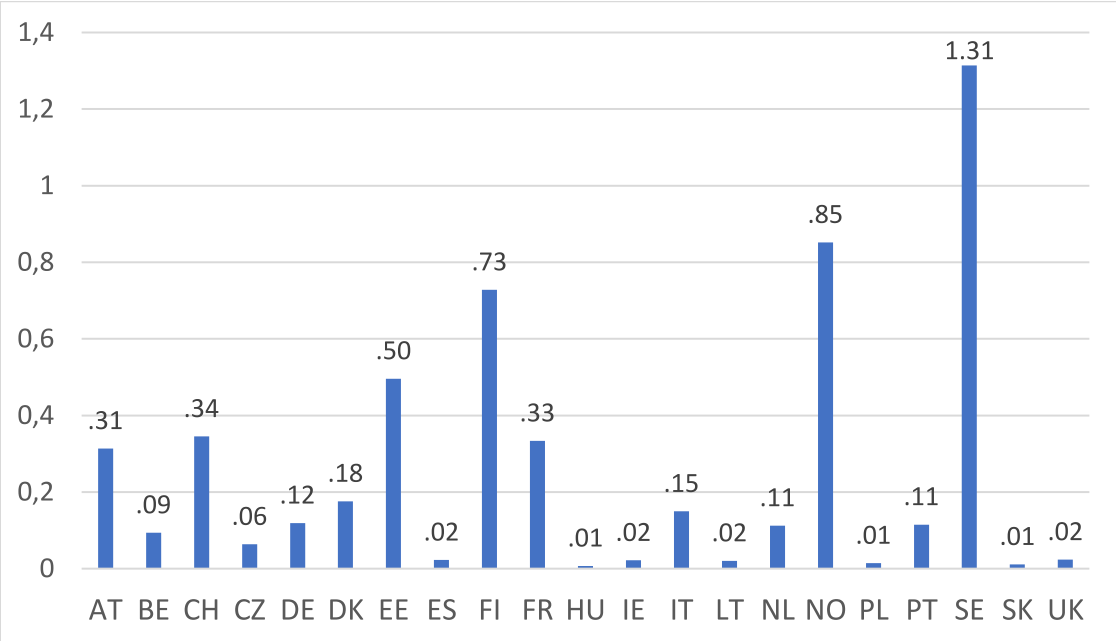

Figure 2. Annual European heat production by HPs per capita in TWh/million residents by country; data HP production from 2013 (EHPA, 2014), data populations from 2015 (the World Bank, 2015b).

During the research it became clear that, at least for the innovation system of HPs, development and diffusion are inherently related in the sense that development focusses almost exclusively on those factors that are inhibiting diffusion. For example, I9 states that the main influence on HP development is market demand. I10 argues that market demand and development are often mirroring one-another. When the market demand for certain HP characteristics is fulfilled, manufacturers stop being incentivized to develop or improve the characteristics any further. The majority of interviewees agrees with these statements, and argue that development mirrors market demands or diffusion bottlenecks (I2, I4, I9, I10). Others take a more careful stance by arguing that the two concepts are somewhat related (I7, I8, I12). In the quantitative analysis, the results are split into diffusion (HP installations) and development (patents) as well, so that the relationship between diffusion and development can be evaluated statistically.

5.2 Descriptive Statistics and Result Tables

Table 4 shows the descriptives for the dataset that was used for conducting the quantitative analysis. It shows the number of cases (countries) for which data was available, minimum values, maximum values, means, standard deviations and variances for all included variables.

Table 4. Descriptive statistics

	N	Min.	Max.	Mean	Std. Deviation	Variance
Total amount of HP's per year per million inhabitants	11	69	13344	4447	5180	26835480
Ground-water HP's per year per million inhabitants	21	5	1864	408	522	272572
Air-water HP's per year per million inhabitants	17	22	1273	353	367	134651
Air-air HP's per year per million inhabitants	15	5	12222	2757	3971	15771384
Patents (inventor)	21	1	106	28	35	1200
Temperature (°C)	21	3	16	8	3	12
Relative humidity (%)	21	61	84	75	5	29
Population density (inhabitants/square km)	21	14	503	144	122	14909
Urban population (%)	21	54	98	75	11	123
Electricity price (€)	21	.094	.308	.189	.060	.004

Before performing the analysis, all regression assumptions where first validated with this data. Even after log-transformations, only the regression on log-transformed air-air HP data complies. A regression is performed for testing the hypothesized relationships for air-air HP's. The non-parametric Kendall's Tau and Spearman's Rho tests are performed to establish the remaining relationships between dependent and independent variables. Quantitative data for hypothesis 1, 2 and 4 was not available. These are only evaluated with qualitative results from interviews and desk research. Table 5 shows a summary of the qualitative results. As can be seen, the hypothesized relationships are not found to be uniformly true.

Table 5. Perceived relationship between included variables and overall HP diffusion by source. Majorities are presented in bold text. Influences on HP development is opposite to the presented table.

Influence	Positive	Neutral/none	Negative
Temperature	**I2, I6-8, I10, I13, D5, D10**	I1, I3	I4, I9
Relative humidity	I6, I9	**I2, I3, I7, I10, I13**	I4, I8, I9, I14
Population density		**I2-5, I8**	I9, I12, I13
Urbanization	I2, I3, I7	I4, I10	**I2, I3, I6, I12, I13, D4**

Electricity price			**I4, I7, I12, I13**
Grid reliability	**I1, I2, I4, I7, I11, D8**		I3, I5, I8
Renovation sector	**I3, I6, I7, I11-13**	I4, I10	I1, I5, I8
Installation sector	I2, I6, I9, I13, D1, D2, D10		**I2-8, I10-13, D3, D7**

Table 6 shows a summary of the quantitative regression results with air-air HP diffusion as the dependent variable. Together, the predictors explain a significant proportion of variance in the amount of European air-air HP installations, $R^2 = .944$, $p = < .001$.

Table 6. Air-air HP regression coefficients

Regression air-air HP diffusion	**Un-std. Coefficients**		**Std. Coefficients**	**t-value**	**Sig.**	**Collinearity Statistics**	
	B	**Std. Error**	**Beta**			**Tolerance**	**VIF**
(Constant)	-32.106	6.644		-4.832	0.001		
Log Temperature	**4.647**	.818	**.85**	5.681	0	.277	3.615
Log Relative humidity[3]	**21.403**	3.844	**.687**	5.568	0	.407	2.457
Log Population density	**-3.985**	.367	**-1.574**	-10.857	0	.295	3.392
Log Urban population	.87	1.597	.053	.545	.599	.654	1.529
Log Electricity Price	**4.601**	.895	**.538**	5.14	.001	.565	1.771

Table 7 shows the results for the non-parametric Kendall's Tau test on the remaining dependent-independent variable pairs. The results for the Spearman's Rho test can be found in Table 9 (Appendix B). Kendall's Tau is argued to be more appropriate in this context because of its higher P-value accuracy with small sample sizes (Statistics Solutions, 2017).

Table 7. Kendall's Tau results

Correlations Kendall's tau		**Temp.**	**Relative humidity**	**Population Density**	**Urban population**	**Elec-tricity price**
All variants	Coefficient	**-.527**	.164	**-.477**	.273	.164
	Sig. (1-tailed)	.012	.242	.021	.121	.242
	N	11	11	11	11	11
Ground-water	Coefficient	**-.641**	**.287**	-.177	.229	-.053
	Sig. (1-tailed)	0	.035	.132	.074	.37
	N	21	21	21	21	21
Air-water	Coefficient	**-.391**	.17	-.066	**.294**	.25
	Sig. (1-tailed)	.014	.172	.355	.05	.081

[3] Relative humidity is inherently correlated with temperature, since air can contain more water when it has a higher temperature. The correlation value and the variance inflation factor have been consulted to determine that multicollinearity is acceptable. Correlation values exceeding (-).9 (Field, 2013) and variance inflation factors higher than 10 (Myers, 1990) are deemed unacceptable. The obtained correlation value of -.437 and variance inflation factor of 2.457 are well within the maximum acceptable limits.

	N	17	17	17	17	17
Patents	Coefficient	**-.388**	.120	.010	**.301**	**.278**
	Sig. (1-tailed)	.007	.225	.476	.029	.040
	N	21	21	21	21	21

5.3 Temperature

In contrast with the hypothesized positive relationship (H5), the Kendall's Tau results for diffusion of all HP variants (N = 21) shows a significant (p = .012) negative correlation with temperature. This could be due to the reduced need for heating when temperatures are higher. In contrast with the usual relationship between diffusion and development, development shows a negative correlation with higher temperatures. It is possible that manufacturers do not see possibilities for increasing diffusion with developments when the need for heating is low to begin with.

A significant negative correlation (p < .001) between ground-water HP installations and temperature as well as between air-water HP installations (p = .014) and temperature was found. For ground-water HPs, this is in line with the negative correlation that was hypothesized (H6) because higher temperatures reduce the need for drilling expensive boreholes to reach sufficient temperature. However, for air-water HPs, a positive relationship was expected (H6) because air-water HPs become more efficient in higher temperatures. Again, a possible explanation is the reduced heating demand in hotter climates.

From the regression on air-air HPs it was found that temperature is positively related to air-air HP diffusion in Europe (p < .001). This confirms the hypothesized relationship (H6). The fact that for air-air HPs the relationship is positive, while for air-water HPs this is not the case, could be due to air-air HPs being related to air-conditioners, which are logically more often applied in hotter climates. The hypothesized positive relationship between patents (development) and temperature was not found to be significant (H5). There seems to be no logical explanation for this.

In the qualitative part of the research, there is consensus amongst interviewees and desk research sources that temperature influences HP development and diffusion (I1-4, I6-10, I13, D5, D10). There is no agreement about the nature of this influence. Most interviewees stress the negative influence of lower temperatures (and therefore a positive influence of higher temperatures) on diffusion for different reasons (I2, I6, I7, I8, I10, I13, D5, D10). First, it is argued that when temperatures are not sufficient, air-source HPs are not viable. At relatively low temperatures their efficiency is lowered due to a lower energy content in the air together with ice buildup on the outside unit (I2, I6-8, D10). Higher temperatures therefore are argued to enable air-source HPs and lessen the need for drilling expensive boreholes. Second, related to this, is the need for small differences between the outside and inside air temperatures (I10, D5). When the difference is too large, efficiency goes down which negates the cost saving that HPs operating at smaller temperature difference enable. I7 states that the applicability of air-source HP's in the Netherlands and Belgium is increased due to sufficient temperatures. At the same time it is reported that difficulties for air-source HPs at lower temperatures stimulate manufactures to develop air-source HPs that are better capable of handling low temperatures, and that relatively high temperatures reduce the need for developing more efficient HPs. In Germany, the availability of a map with climatic conditions and the corresponding HP size that is required is said to have a positive influence on HP diffusion (I13).

One source reports that temperatures and HP diffusion are inversely correlated (I9). I9 mentions the fact that colder temperatures increase the heating demand of residential buildings, and therefore the use of HPs. This could reduce the need for HPs in southern Europe where average temperatures are higher. For example, when temperatures are above 20 degrees Celsius, the heat loss of the house to the environment will be reduced to zero when 20 degrees Celsius is also the required indoor temperature. Furthermore, because the influence of outside air temperature is sometimes not sufficiently accounted for, undersized HP's are deployed that do not have sufficient heating capacity in colder periods (I4). This has a negative influence on the legitimacy of the technology. The influence of temperature thus is of a multifaceted nature. This could also be the reason that some sources acknowledge that temperature is of importance but are hesitant to specify the nature of this influence (I1, I3).

All qualitative results combined, the hypothesized relationship between temperature and HP diffusion (H5) is confirmed by a majority of sources. Higher temperatures are positively related to HP diffusion due to higher efficiencies, according to a majority of qualitative sources. For development, the hypothesized relationship is not confirmed (H5), since higher temperatures reduce the pressure on manufacturers to achieve higher efficiencies at low temperatures. The hypothesized relationship for air-source and ground-source HP diffusion specifically is also confirmed (H6). Higher temperatures are positively related to the diffusion of air-source HPs, and negatively related to ground-source HPs because when temperatures are sufficient, there is no need to drill boreholes for ground-source HPs. Again, the hypothesized influence on development is not confirmed (H6).

5.4 Relative Humidity

In the Kendall's Tau test, a significant (p = .035) positive correlation between ground-source HPs and relative humidity was found. This positive relationship between relative humidity and ground-source HP diffusion was also hypothesized (H8), because a high relative humidity increases the problem of frost buildup on air-source HPs, increasing the viability of more expensive ground-source HPs. Relative humidity was not found to be significantly related to air-water HP diffusion, HP diffusion overall or HP development, while a negative relationship was hypothesized for all three (H7 & H8). It is possible that consumers do not let the average relative humidity play a role in their decision to install an HP or not, but do so in the decision of what HP to install.

The results from the regression show that relative humidity significantly increases the amount of air-air HP installations in Europe ($p < .001$). This disproves the hypothesized relationship (H8), stating that higher relative humidity frustrates the diffusion of air-source HP's due to increased problems with frost buildup on the outside units.

For the qualitative part of the research, the majority of sources agree that humidity does not have a large influence on either development or diffusion of HPs (I2, I3, I7, I10, I13). However, I2 and I10 note that the Czech Republic and Denmark are not very humid. They acknowledge that in more humid countries this could be a problem for diffusion. I13 notes that freezing occurs in Germany, but that the earlier mentioned climatic map also accounts for the extra heating capacity needed due to varying humidity levels in different parts of Germany.

Some sources argue that the frost buildup on the outside units of air-source HPs negatively influences HP diffusion (I4, I8, I9, I14). I4 and I9 argue that the freezing requires consumers to install a HP that is 10 percent larger than the required heating capacity. This larger capacity is needed to compensate for the time that the HP is defrosting. During this time the heating capacity drops to zero. I8 argues that the climatic conditions in the UK are especially poor in this case. Humidity is almost always high, and temperature often lies just above zero degrees Celsius. Therefore it would be cold enough for the outside unit of air-source HPs to freeze, but not cold enough for the humidity to drop.

However, some sources also perceive a positive side to high relative humidity (I6, I9). For example, the problem of frost buildup would require manufacturers to develop more efficient solutions, stimulating development in Sweden (I9). And although it falls outside the scope of the current research, it is interesting to note that for exhaust air HPs, indoor relative humidity increases the latent energy available in the outgoing air, increasing the heating capacity of exhaust air HPs (I6).

Overall, the hypothesized relationship between relative humidity and HP development and diffusion is not confirmed (H7). Higher relative humidity is not related to HP development and diffusion according to a majority of qualitative sources. The hypothesis stating that relative humidity negatively influences air-source HP development and diffusion and positively influences ground-source HP development and diffusion (H8) is also not confirmed in the qualitative analysis.

5.5 Population Density

In the Kendall's Tau test, a significant ($p = .021$) negative correlation between HP diffusion overall and population density was found, confirming the negative relationship that was hypothesized (H9). No significant relationship between population density and ground-water HP diffusion, air-water HP diffusion or overall HP development was found. For development, a negative relationship was hypothesized (H9). The regression shows that air-air HPs are also negatively related to higher population densities ($p < .001$), although no hypothesis was formulated for the relationship between this specific type of HP and population density.

Most qualitative sources state that population density does not have a large effect on HP development and diffusion (I2-5, I8). I4 sees a possibility that density becomes more problematic for diffusion in the future, but it is unclear why. Although I5 perceives no influence of population density in Denmark, the option of this being a bigger problem in more dense countries is not rejected. I8 argues that a perceived problem of population density with ground-source HPs is not justified. Although it would be common for actors to think that drilling in high density areas is problematic, I8 has conducted a study in collaboration with a well-known university that disproves this. With proper planning, op to 95 percent of building heating loads could be accounted for with ground-source HPs in London and Beijing.

Other respondents state that population density is inversely related to HP diffusion (I9, I12, I13). Like I8 predicted, I9 perceives the borehole drilling for ground-source HPs to be problematic due to obstacles in the ground. I12 argues that in highly populated areas, the space availability for outside units of air-source HPs is low. I13 states that HPs are especially installed in new build areas in Germany. The problem with these areas would be the short distance to neighbors, combined with strict noise pollution regulation on neighboring buildings.

The hypothesized inverse relationship between relative humidity and HP development and diffusion is not confirmed (H9). Higher population density is not related to HP development and diffusion according to a majority of qualitative sources.

5.6 Urbanization

For urbanization, a negative correlation with overall HP diffusion and HP development was hypothesized (H10). However, the Kendall's Tau test returned no significant results for overall HP diffusion and a significant ($p = .029$) positive correlation with HP development. It could be that the hypothesized negative effect of urbanization is too small to detect with the relatively small sample size of this research. A possible explanation for HP development being positively related to urbanization could be that HP development is stimulated more by people living in cities than that it is related to HP diffusion (as argued in the beginning of this chapter). A significant ($p = .05$) positive correlation between air-water HP diffusion and urbanization was found, although no relationship was hypothesized for this specific HP type. It could be that the visibility of air-water HPs in cities is heightened, leading to faster diffusion.

In the regression on air-air HPs, and in the Kendall's Tau test for ground-water HPs, no significant relationship was found with urbanization. No hypotheses were formulated for these specific types of HPs as well.

In the qualitative analysis, most sources argue that problems are similar to the problems associated with high population density. Although the effect is still not perceived to be very large, here, the majority tends to classify the influence on HP diffusion as negative (I2, I3, I5, I6, I12, I13, D4). The availability of enough space to place an outside unit for air-source HPs is limited (I12, I13). Related is the problem of noise production with outside units of air-source HPs (I2, I5, D4). A problem for HP diffusion specifically for cities would be competition from district heating networks (I6). The problems that are associated with obstacles in the ground when drilling boreholes would become especially apparent in dense cities (I9) although I8 opposes this. Also specifically with ground-source HPs, the noise from drilling boreholes could be a disturbance according to I3.

Furthermore, I4 and I10 argue that the influence of urbanization is negligible. I10 does acknowledge that, for example, the noise from outside units could be more of a problem in countries with larger and more dense cities than Denmark. I6 notes that in the Netherlands, there is the tendency for old city centers to remain dependent on gas networks. This does not mean that no HPs are installed. Hybrid HPs that are composed of an air-water HP combined with a gas boiler would be the go-to option here.

Some do see positive influences related with higher urbanization. The noise problem with outside units would stimulate manufacturers to develop more quiet systems (I2, I7). Also, in Poland, the electricity grid in urban areas would be better developed, stimulating the diffusion of HPs (I3).

The hypothesized inverse relationship between urbanization and HP diffusion (H10) is confirmed in the qualitative analysis. Higher population density frustrates the diffusion of HPs according to a majority of qualitative sources. However, for development, this causes an inclination for developing HPs that produce less noise, take up less space, or fit better in urbanized areas due to other innovations.

5.7 Electricity Sector

5.7.1 Electricity Prices

The regression shows that the cost of electricity significantly increases the amount of air-air installations in Europe ($p = .001$), although no relationship was hypothesized to exist for this specific type of HP. It could be that higher electricity prices increases the incentive to switch from in-effective air-conditioners and electrical heating to air-air HPs.

In the Kendall's Tau test, overall HP development returned a significant ($p = .040$) positive correlation with electricity prices while a negative relationship was hypothesized (H3). No significant results were obtained for the relationships between electricity prices and overall, ground-water or air-water HP diffusion. For the latter two, this was also not hypothesized. The relationship on overall HP diffusion could be in-significant due to two contrasting influences. On the one hand, lower electricity prices mean that HPs can more easily achieve larger savings compared to, for example, gas and oil fired alternatives. At the same time, when a country uses traditional low-efficiency electrical heating appliances, a higher electricity price increases the incentive to switch to higher-efficiency appliances such as HPs. Together, these influences could neutralize each other.

In accordance with the hypothesized relationship (H3) electricity prices are perceived to be inversely related to HP diffusion (I4, I7, I12, I13) in the qualitative analysis. In Belgium, Germany and Hungary, the price of electricity is very high compared to alternatives such as gas (I4, I7, I13). This requires HPs to be extremely efficient before any cost savings can be achieved. Hungary and Italy have special electricity tariffs for the heating season and heating appliances respectively (I12, I4). Since these lower tariffs are thought to have a positive influence on HP diffusion, there is agreement on the inverse relationship of electricity prices with HP diffusion.

5.7.2 Grid Reliability

The results on the qualitative relationship between the reliability of the electricity grid and HP diffusion are mainly positive (I1, I2, I4, I7, I11, D8), confirming the hypothesized relationship (H4). Overall, the grid is thought to be stable enough, and peak loads are not perceived to be problematic, enabling HP diffusion (I1, I2, I4, I7, I11). In Germany, current HP installations are already smart grid ready (I7), meaning they can reduce peak loads if necessary and utilize renewable energy when it is available. Research in Finland shows HPs do not increase peak loads at all when countries have a large dependence on traditional electrical heating systems that are less efficient (D8).

However, some countries experience negative effects from the electricity grid on HP diffusion (I3, I5, I8). In Poland, as was mentioned before, less urbanized areas have a less developed electricity grid (I3). Also, the electricity grid is less developed in eastern Poland. In the UK, there are concerns in the electricity generation and distribution sectors about the mass deployment of HPs (I8). The costs to adjust are perceived to be high, although I8 does not agree with this. In Norway, the electricity grid reliability sometimes is a bottleneck causing less HPs to be installed (I5).

Overall, the hypothesized relationship with diffusion (H4) is confirmed in the qualitative analysis. Electricity grid reliability is sufficient for consumers to adopt an electricity based heating solution, leading to heightened diffusion and removing the incentive for further development. The influence of the electricity grid was not evaluated quantitatively.

5.8 House Energy Labels

The implementation of house energy labels is thought to be positive for residential HP diffusion by a majority of qualitative sources (I3, I6, I7, I11, I12, I13). I12 elaborates that this is due to a positive relationship between house energy labels and energy costs, with a “higher” or better label indicating lower energy consumption and higher house value, at least in Italy. It is therefore interesting for home-owners to install a HP, since its effect on a house its energy efficiency is acknowledged in the energy label.

Some sources also describe energy labels as having a neutral or no influence on HP development and diffusion (I4, I10). For example, I4 from Hungary describes two main reasons for this. One, existing houses mainly have energy labels of E, F and worse. Due to these relatively bad labels, the focus is sometimes believed to be better put on thermal insulation, before HPs become interesting. Second, in new houses, energy labels such as A and A+ can be reached with less capital when good insulation together with efficient gas boilers are applied. Although the sources describe this as a neutral influence, it can be argued that this would have a negative influence on HP diffusion, and therefore a positive influence on HP development.

Finally, three actors would characterize the influence of house energy label implementation on HP diffusion more negatively (I1, I5, I8). In Norway the label would be marketed badly, causing ignorance at the consumer level (I5). Also, people would care more for other aspects when, for example, buying a house. In Ireland, the system is thought to be too complicated, while at the same time it would be lacking in the sense that the theoretical energy performance is not cross-referenced to the actual energy performance on-site (I1). In the UK, I8 is critical about the way the labelling system is managed. For establishing energy labels, the “Standard Assessment Procedure” (SAP) is applied, which is managed by an organization called “BRE”. The label is partly based on the carbon intensity of different energy carriers. The main criticism of I8 is that the carbon intensity of electricity is much lower than is stipulated by BRE. Due to coal fired power stations being shut down and renewable energy installations being more commonly used, the carbon intensity is sometimes only 25 percent of that what it used to be. This lowered carbon intensity has not been adjusted in the SAP, leading to a much higher theoretical carbon intensity for HPs compared to what it would be when regular updates had taken place.

The hypothesized negative influence of house energy labels and HP development and diffusion due to implementation issues is not confirmed (H1). Although some countries perceive problems with the energy label its implementation or marketing, overall, the use of house energy labels was found to be positively related to HP diffusion. The positive effect on diffusion would partly diminish the incentive of manufacturers to develop more efficient systems.

5.9 Installation Sector

A large majority agrees that the installation sector frustrates HP diffusion (I2, I3, I4, I5, I6, I7, I8, I10, I12, I13, D7). The typical installation company being small is given as a primary reason for this (I2, I3, I5, I6, I7, I8, I10, I12, I13). The small size would lead to a limited time for training and education and corresponding skill level (I2, I3, I5, I8, I12). Selling traditional heating systems such as oil burners and gas boilers is often preferred over HPs because installers have more experience with these traditional technologies (I5, I6, I7, I12, I13) and have no shortage of work (I13). Installers often offer a limited number of brands, which do not always include the optimal HP for the customer (I10). In the past, bad installations have damaged the reputation of HPs in Poland. In Hungary it is argued that many of the installers that do have a high skill level emigrate towards eastern Europe (I4). In Italy a lack of sales techniques leads to installers not being able to convince consumers to switch from gas heaters to HPs (I12). And although 89 percent of the air-conditioning installation sector in Spain knows about HPs, only 63 has worked with them (D3).

Some also address the positive side of the installation sector (I2, I6, I9, I13, D1, D2, D10). Specifically for the development of HPs, the low-skilled installation sector is a stimulus to develop plug and play systems that are easy to install (I2, I13). For the Netherlands, I6 sees a trend towards larger installation companies that reserve more time and resources for training and education. In Sweden, plumbers are described to be very skilled in HP installation (I9). Also, Sweden has an independent complaints board representing consumer interests after sales. The board plays an active role in increasing the quality of the installation sector by disciplining installers when bad installations are reported. Not only does this stimulate consumer confidence, it also drives producers to stimulate the quality of their installation network and incentivizes installers to deliver high-quality HP systems. Furthermore, Belgium and France have specialized education programs for increasing the quality of their installation sectors (D2, D10).

The hypothesized negative influence of installation sector firm size on HP development and diffusion due to installation firms being too small is confirmed for HP diffusion (H2). The small size of installation sector firms was found to frustrate the diffusion of HPs according to a majority of qualitative sources. Larger firm sizes would likely increase the available time and resources for training and education. Regarding HP development, the negative influence of the installation sector creates an incentive for manufacturers to develop systems that are easier to install (a positive influence)

5.10 Summary of Results

Table 8 shows a summary of both the hypothesized relationships, the qualitative results, and the quantitative results for HP diffusion and development. The fact that there are few similarities between the quantitative and qualitative results proves the added value of using a mixed method approach. See the discussion (Chapter 6) for an in-depth analysis of the similarities and differences in the outcomes of the mixed-method approach.

Table 8. Summary of all results

	Hypothesized relationship	Obtained qualitative results diffusion (development)	Obtained quantitative results diffusion	Obtained quantitative results development
H1 – Implementation of energy labels	Negative	Positive (negative)	N.a.	N.a.
H2 – Small installation sector firm size	Negative	Negative (positive)	N.a.	N.a.
H3 - Electricity price	Negative	Negative (positive)	No significant relationship	Positive
H4 - Grid reliability	Positive	Positive (negative)	N.a.	N.a.
H5 - Temperature (HPs overall)	Positive	Positive (negative)	Negative	Negative
H6 - Temperature (specific HP influences)	Positive for air-source, negative for ground-source	Positive for air-source, negative for ground-source (negative for air-source, neutral for ground source)	Positive for air-air, negative for air-water, Negative for ground-source	N.a.
H7 - Relative humidity (HPs overall)	Negative	Neutral (neutral)	No significant relationship	No significant relationship
H8 - Relative humidity (specific HP influences)	Negative for air-source, positive for ground-source	Neutral (neutral)	No significant relationship for air-water, positive air-air, Positive for ground-source	N.a.
H9 - Population density	Negative	Neutral (neutral)	Negative	No significant relationship
H10 - Urbanization	Negative	Negative (positive)	No significant relationship	Positive

5.11 Additional Results

5.11.1 Competing Energy Carriers and Heating Systems

As has been noted with the earlier results, competition from alternative heating sources and systems influences HP development and diffusion in a variety of ways. For example, it causes manufacturers to focus on ease of installation in order to make it easier for installers to switch from traditional systems to HPs. However, competition between HPs and alternatives has been found to have an even larger influence than has already been described. For example, when looking at the country that has the highest HP diffusion per capita, it is not likely that it is a coincidence that there is no gas infrastructure except for the west coast (I9). And when it is available, it is expensive. This positively influences the business case for HPs.

This is in sharp contrast with Belgium, Germany and Hungary, where electricity is relatively expensive and gas cheap (I4, I7). Also, at least in the UK, the history of using gas as the main energy carrier for heating has reportedly given the involved actors the chance to integrate themselves in several power structures (I8). This would cause lobbying practices to be exceptionally well heard by, for example, the government. The gas infrastructure in the UK still being subsidized by the government is a possible result of this. Finally, next to gas boilers, oil burners (I13), pellet stoves (I5, D2) and district heating networks (I5, I9, D2) are competing heating systems.

However, companies producing competing heating systems such as gas boilers do not exclusively frustrate HP development and diffusion. One example is the use of hybrid HPs in the Netherlands (I6). These are air-water HPs combined with traditional gas boilers. The main advantage of this technological development is that at lower temperatures, the HP can switch to the gas boiler so that it does not have to operate with lower efficiency and capacity. Another positive aspect of competition is that incumbent companies see the opportunities of HPs, as many have started producing HPs themselves (I12).

5.11.2 Complementary Technologies

Several technologies also seem to benefit HP development and diffusion. To begin with, a HP works most efficiently when the difference between the indoor and outdoor heating temperature is as small as possible (I5, I6, I7, I12). Therefore, technologies that facilitate low heating temperatures, such as low-temperature radiators, convectors and floor heating stimulate the diffusion of HPs. At the same time, high-temperature heating demands are said to stimulate the development of HPs that can achieve this at reasonable efficiencies (I2).

Furthermore, better insulation and air-tightness would be beneficial for HP diffusion (I4, I10, I12). Buildings with a lower total energy demand are currently better suited for HPs since smaller HPs are less expensive and more efficient. I3 also noted that infrared technology can be used to reduce the total heating demand for HPs.

Finally, PV systems would be beneficial for HP diffusion since HPs can utilize the electricity that is produced by these systems (I3, I12, D4, D5), reducing the amount of electricity that needs to be fed into the electricity grid by PV systems and reducing the electricity demand from the grid for HPs. Related to this is the complementary use of (thermal) battery systems (D4). Battery systems can story electricity or heat for times that the heating demand is high and supply is low, further reducing the impact on the electricity grid and allowing for smaller HPs to be used.

5.11.3 System Cost, Efficiency and Payback Period

One aspect that has been found to be a major driver for overall HP diffusion (and for air-source development) is efficiency, or COP (I1-4, I6, I9-13, D1, D4, D5, D7, D9, D11). Since the COP of air-source HPs have increased compared to ground-water HPs, less consumers invest in the extra expense of drilling boreholes and stick to air-source HPs (I2, I3, I4, I9). The COP's of air-source HPs having increased faster than that of ground source HPs is another confirmation that development focused on those factors that are inhibiting diffusion, since in the past air-source HP COP's were sometimes considered to be too low to be economically viable over alternative heating technologies. The efficiency or COP of a HP is particularly important because it directly influences the return on investment and payback period, another important aspect (I5, I8, D9). D9 states that a return on investment of more than 10 percent per year is very common, and that this is a major driver for HP diffusion. A return on investment that is too small and long payback periods would be a blockade for older consumers to invest in HPs (I5). If the system cost is not paid back in cost saving within one's own lifetime, it would be less interesting to pursue.

The system cost is the second part, next to efficiency or cost savings, that determines how large the return on investment or how long the payback period will be. Many sources believe this to be another important factor for HP development and diffusion. Initial costs can be a major blockade for adoption in eastern European countries such as the Czech Republic (I2), Poland (I3), Hungary (I4) and Lithuania (D11). In these countries, initial cost is so important that it can be hard to educate consumers about the long term benefits. However, also in other European countries the initial system cost is mentioned as one of the most important influences on HP diffusion and development (I1, I6-9, I12 I13, D4, D12). Because the influence of initial system cost is so big, there would be a problem involving cheap, low-quality productions from companies that produce in the far-east (I2, I4).

6. Discussion

This Chapter aims to provide a deeper understanding of the implications of the findings of this thesis. First, the limitations of the research are elaborated upon in Section 6.1. Findings are discussed in Section 6.2, starting with the relationship between diffusion and development in Section 6.2.1. In the sections thereafter the result of each individual context condition is discussed in further detail. For each context condition the relevance of the findings is discussed, the results are related to similar studies, the limitations of specific context conditions are discussed together with the theoretical implications and possible future research avenues are presented (Section 6.2.2-6.2.9). Policy implications are discussed in Section 6.3.

6.1 General Limitations

Some limitations of the research have to be acknowledged. One limitation is situated in the use of patents as an indicator for development. While this is done more often (Hekkert, 2007), it is not without controversy. While patents can indeed be indicators of inventions, firms also file patents strategically, for example to enforce appropriability (Chesbrough, 2003; Laursen & Salter, 2006; Teece, 1986) or to block competitors from developing innovations in a defensive patent portfolio (Guellec, Zuniga, & Martinez, 2008). Furthermore, patents do not capture development as a whole, since not every developmental effort is patented (Klevorick et al., 1995; Laursen & Salter, 2006; Levin et al., 1987), and other mechanisms for appropriating value from innovation such as secrecy, lead times, first mover advantages and complementary capabilities are applied to a different degree across firms and industries (Cohen, 2002; Hussinger, 2006).

When interpreting the quantitative result for air-air HPs, one also has to be aware of the implications of log-transforming data. Some researchers argue that statistical tests performed on log-transformed data are not relevant for the original non-log-transformed data (Feng et al., 2014). Even when true (log-transformations are common practice), the implications for this research are small, since log-transformed data is only used for the regression on air-air HPs, a relatively small partition of the research.

Furthermore, some difficulties were experienced with data collection. Due to an exceptionally low response rate with interview requests, interviews could not be performed in every European country. While some input was collected for these countries by performing desk research, the extent of the findings is limited in the sense that not all variables are qualitatively accounted for in these countries. The advantage of doing interviews clearly shows, since the interviewer can then specifically ask for the influence of every variable, while when doing desk research, obtaining a result for every variable has proven to be more difficult.

Finally, some limitations have become apparent with data availability for the quantitative analyses. For example, while diffusion data was available for the period 2005-2014 (although some data gaps where present), electricity prices could not be averaged over this time period due to a lack of data. Therefore there is a discrepancy in the dataset in terms of the period for which data was collected, since electricity prices have also changed over time. Finally, due to a lack of quantitative data for some variables, the research could not be performed both qualitatively and quantitatively. Since this was the main method of triangulating data, data triangulations was not possible in these cases.

6.2 Discussion of Findings

6.2.1 Diffusion and Development

The results show that development takes place along the lines of factors that are inhibiting the diffusion of HPs (except with temperature, see Section 6.2.2). A clear example of this is that of noise production from outside units of air-source HPs. Over the last years significant improvements in this area have been reported, reducing the incentive for further noise reduction. However, especially in Germany, due to strict regulation of maximum noise pollution on neighboring facades, noise production sometimes still frustrates the diffusion of air-source HPs. The negative influence of noise on air-source HP diffusion is at the same time reported to be a major focus of development in Germany due to strict regulation, while other countries report that the focus on noise production reduction has faded due to sound levels being considered to be acceptable and due to the absence of (strict) regulation.

In the quantitative analysis, for all context conditions, either the influence on diffusion or development was not significant (except for temperature). It would be valuable for future research to further explore the statistical relationship between diffusion and development in order to shed more light on the qualitative findings. Even more so because one can argue that development is a prerequisite for diffusion. A technology first has to developed before it can be produced and diffused. Could it be profitable for long-term technology diffusion and performance to frustrate diffusion on the short-term by setting high standards, in order to incentivize further development? This is not unlikely when one realizes that the notion that pressure can stimulate firms to innovate is nothing new (Boone, 2000). Even Porter (1990) argues that at the nation level, demand conditions (relatable to diffusion conditions) are one of the major forces that enable certain countries to consistently innovate (relatable to development) at a higher pace than others. Future research could aim to answer these questions by conducting a statistical analysis with a larger sample size, preferably including multiple cross-industry technologies developed by firms in different countries. It is also advisable for this research to collect data on the use of other appropriability mechanisms.

6.2.2 Temperature

Although many findings of the current research are inconclusive in the sense that different results are found in the quantitative and qualitative analyses, often there are logical explanations available. For the influence of temperature on overall HP diffusion, for example, the qualitative research indicated an positive relationship in line with the hypothesized relationship (H5), but in the quantitative analysis a significant negative relationship was found. A possible explanation for this is that with higher average annual temperatures, the heating demand of houses is reduced to such a degree that consumers do not see the need for installing capital intensive HPs, and that qualitative sources do not perceive this effect to be as large as the increased efficiency of HPs with higher temperatures.

It has to be noted that the current methodology for including temperature is somewhat limited. Future research could try to account for the difference in importance between certain temperature ranges, and temperature fluctuations within a year. For example, at temperatures below 5 degrees Celsius, the HP efficiency is reduced more than the efficiency drop in the range of 5 to 15 degrees Celsius for air source HPs, because of frost buildup on outside units. And in the 15 degree and up range, temperatures are already quite habitable, reducing the need for additional or extremely efficient heating. Future research could include the days or percentage of time that country climates reside in these ranges.

Regardless of the direction of the influence and method for inclusion, both the quantitative and qualitative analyses agree that temperature indeed has an effect on TIS performance. As for theoretical implications, this acts as a first confirmation that the environmental CS can add value to the TIS framework. Furthermore, the differences between qualitative and quantitative outcomes demonstrate the advantages that the mixed-method approach has proven to offer. One peculiarity is that in all other context conditions, development focusses on bottlenecks for HP diffusion, but temperature has shown a negative correlation with diffusion as well as development. It is possible that when diffusion is negatively influenced due to a low heating demand, development is as well, since no developmental effort can justify a heat pump when there is no heat demand to begin with.

6.2.3 Relative Humidity

Relative humidity was not found to be of any effect on overall HP diffusion or development in both the qualitative and quantitative results, while a negative influence was hypothesized (H7). Although qualitative sources acknowledge that relative humidity magnifies the problem of frost buildup, the majority does not perceive a large effect on either HP diffusion or development. It is possible that future research with a larger sample size is able to detect a significant result for overall diffusion. This is likely because in the statistical analysis testing the influence of relative humidity on specific HP variants, air-air and ground-source HP diffusion are positively and significantly influenced by higher humidity levels. This could be an indication that relative humidity only has an effect on what HP to buy, and not on the decision whether to buy a HP or not.

Although the significant influences on specific HP variants again prove the theoretical importance of the environmental CS its influence on TIS performance, there are some reservations. While for ground-source HPs the positive influence was hypothesized (H8) and found, since these do not experience any problems with frost buildup, the positive influence on air-air HP diffusion was hypothesized as a negative influence due to increased problems with frost buildup. An explanation for this result is not easily found. Since relative humidity is inversely related to temperature (but not too much to be excluded from the analysis), relative humidity is on average lower in countries with higher temperatures. In these warmer and less humid climates, such as Spain and Portugal, air-conditioners are also more common. The vast majority of air-air HPs are in fact air-conditioners at the same time, implying that there is a higher affinity with similar technology in warm countries (with low relative humidity). However, the results show the opposite, since these less humid countries have a lower rate of air-air HP diffusion.

A second possibility would be that since in these countries with lower humidity many people already have air-conditioners, they don't see the point of replacing these with air-air HPs (since they have a low heating demand) or are waiting until their air-conditioner stops functioning. However, it is then impossible to justify the statistical result of temperature showing significantly higher diffusion of air-air HPs in warmer climates. This means that either significant relationship does not exist in reality (a type I error; extremely unlikely due to a p-value of $<.001$), or that additional factors play a role in explaining this. Future research could aim to clarify this.

6.2.4 Population Density

While the hypothesized influence of population density on HP development and diffusion was negative, only the negative influence of population density on HP diffusion was confirmed in the quantitative analysis (H9). The majority of qualitative sources do not experience population density to be of influence on either development or diffusion. The discrepancy between qualitative and quantitative results could indicate that population density is more of a problem for HP diffusion than qualitative sources perceive it to be. A qualitative study that purposely selects cases with contrasting population densities can possibly confirm the obtained quantitative relationship for HPs. Studies looking at HPs (Hewitt et al., 2011; Kieft, 2017) and other renewable energy technologies (Tsoutsos, Frantzeskaki, & Gekas, 2005) have confirmed that the importance of aspects such as noise, land use and visual impact is greater with higher population density. These studies, together with the quantitative result obtained here, again suggest that the possible influence of environmental context conditions on technology performance cannot be ignored in a TIS analysis.

6.2.5 Urbanization

Surprisingly, the influence of urbanization shows different results compared to population density, although the two context conditions are related. In line with the hypothesized relationship (H10), a majority of qualitative sources do see a negative influence on HP diffusion due to problems with space availability or noise production, while the quantitative results show no significant relationship for HP diffusion. It is possible that the sample size of the analysis could be simply too small to detect a significant negative influence on diffusion. However, the influence of urbanization on HP development was significant and positive. Noting the qualitative outcome, it is possible that the perceived negative influence of urbanization on diffusion is enough to create a significant positive reaction in development. The possibility of the current sample size being too small, causing the quantitative influence of urbanization to be non-significant is however also likely. Especially when one looks at earlier studies on HP's (Hewitt et al., 2011; Kieft, 2017) and the negative influence of urbanization on the diffusion of other renewable energy technologies (Pedersen & Waye, 2007). Although the results are not fully conclusive, the influence of urbanization and therefore that of the environmental CS on (parts of) the TIS is confirmed both in a qualitative and quantitative manner.

6.2.6 Electricity Prices

The final independent variable that has been evaluated both quantitatively and qualitatively is that of electricity prices. The majority of qualitative sources argue that electricity prices have a negative influence on HP diffusion due to the lower cost saving compared to alternative energy carriers and a positive influence on HP development due to the need for higher COPs when electricity prices are high. For diffusion, the obtained negative influence is in line with the hypothesized influence (H3). In the quantitative analysis, only a positive influence of electricity prices on HP development was found. This is in line with the obtained qualitative results, but not with the hypothesized negative influence of electricity prices on HP development. This means that although the hypothesis has not been fully confirmed, the results do indicate that the price of electricity, and therefore the sectoral CS, is important for the performance of the HP TIS in Europe. As for theoretical implications, it is possible that these findings are true in different contexts as well, but future research still has to confirm this (as is true with other findings in the research as well).

6.2.7 Grid Reliability

Electricity grid reliability was included as a second indicator of the electricity sector. Due to absence of proper quantitative data indicating grid reliability, its influence has only been evaluated qualitatively. In the qualitative results, the hypothesized influence of grid reliability on diffusion has been confirmed (positive, H4). Likely due to the grid being perceived to be reliable enough, no qualitative source stated that grid reliability stimulates producers to develop innovations that make HPs more capable of handling less reliable grids. Although the hypothesis has only been confirmed for HP diffusion, the importance of grid reliability on HP TIS performance is confirmed. This also confirms the importance of the electricity sector and the sectoral CS on TIS performance, implying that future TIS studies should assess whether to include sectoral context conditions.

6.2.8 Energy Labels

The influence of house energy label implementation on HP development and diffusion was only evaluated qualitatively. While a negative influence of energy labels was hypothesized (H1) due to issues with implementation, the majority of consulted sources considers the labels to have a positive impact on HP diffusion. Although sometimes the implementation of the labels is questioned, with similar criticisms as Kieft (2017) has with implementation in the Netherlands, the overall influence on diffusion is still considered to be positive. This indicates that in the influence of house energy label implementation is not as frustrating for HP diffusion and development as was hypothesized, and that the results from Kieft (2017) cannot be generalized to Europe. However, the majority of sources still agrees that there is an influence, confirming the importance of the sectoral CS on HP TIS performance in Europe.

6.2.9 Installation Sector

It was hypothesized that the small size of installation sector firms has a negative impact on HP diffusion and development, because the small size would limit the firms available resources to adjust to a changing heating technology such as HPs (H2), and due to a lack of diffusion, development would be less profitable as well. Regarding HP diffusion, this was indeed almost uniformly found to be true, except in Sweden. In Sweden, a long history of plumbers installing HPs has increased their skill level over time. In the rest of Europe, installation sector firms are perceived to be very small according to a majority of sources, and this is thought to create multiple problems. Not only does this limit the available resources for training and education, the small installation firms also offer a limited amount of HP brands. This would result in non-optimal installations, as consumer choice is limited after choosing an installer. Specific for diffusion, the influence of the fragmented and low-skilled installation sector was deemed to be very positive. Manufacturers would actively strive for developing plug-and-play systems that reduce the required skill level from installers. The results confirm the importance of the sectoral CS on TIS performance.

6.3 Policy Recommendations

The results show that European policy makers should be aware of the possible implications that context conditions have when using a TIS to create a policy framework for residential HPs. An example is the influence of temperature on TIS performance. Since a traditional TIS analysis does not account for the influence of temperature as context, reasons for slow diffusion or development are likely to be interpreted as a (partially) dysfunctional functional pattern. The current research shows that it is also possible that the cause lies in a temperature that is too high for consumers to be able to justify the investment in a costly heating technology such as HPs, and not in the functioning of the TIS itself. Similarly, when policy makers detect that development is thriving, a traditional TIS analysis would attribute this to a well performing functional pattern or a well performed function such as 'knowledge development and diffusion'. The present research shows that this could be simply attributable to a high percentage of the population living in cities, causing the need for smaller, quieter or new HP variations. Similarly, urbanization, energy label implementation, small installation sector firms, electricity prices and grid reliability could be context conditions that influence diffusion and development, implying that policy makers should account for these influences when interpreting the results of a TIS analysis. Only relative humidity is suggested to be of little importance for development and diffusion, meaning that this influence does not has to be accounted for.

7. Conclusion

In the present research an attempt has been made to further investigate the influence of the environmental and sectoral CSs on TIS performance. The case of HPs was deemed as a good example due to the technology relying on environmental resources such as temperature and being related to several sectors. Although the importance of the CSs on HP performance has been confirmed, the precise nature of the influences has proven to be multifaceted.

To begin with, diffusion and development where hypothesized to be similarly affected by the different contextual influences since heightened diffusion increases the market size which means increasing the available capital for development would be justified. Results indicate that the opposite is true. Diffusion bottlenecks act as pressures on manufacturers to improve or adjust. The pressures of staggering diffusion therefore act as an inclination for development. This creates an inverse relationship between development and diffusion, as is reflected without exception in the results. This causes all hypotheses to be rejected.

The hypothesized influences of installation firm size (negative, H2), electricity price (negative, H3), grid reliability (positive, H4) and urbanization (negative, H10) have been accepted with regard to their influence on HP diffusion in Europe although the quantitative analysis showed no significant result for electricity prices and urbanization. Installation firm size and grid reliability were not evaluated quantitatively.

The hypothesized influences of energy labels (negative, H1), temperature (positive, H5; varying for specific HPs, H6), relative humidity (negative, H7; varying for specific HPs, H8) and population density (negative, H9) are rejected, although the hypothesis for the influence of temperature on specific HP variants has been fully confirmed in the qualitative analysis, and partly confirmed in the quantitative analysis for ground source HPs and air-water HPs.

Concluding, it can be stated that although the influences of the environmental and sectoral CSs were often not in line with expectations, their importance for TIS performance is not debated. Additionally, results regarding the (non-)similarities between TIS diffusion and development may prove to be valuable for policy makers in understanding how diffusion or development can be stimulated, although more research is needed to determine the exact extent to which development focuses on factors inhibiting diffusion.

References

Ackermann, T. (2005). Wind power in power systems. John Wiley & Sons.

Adner, R. (2006). Match your innovation strategy to your innovation ecosystem. Harvard business review, 84(4), 98.

Asociación de Fabricantes de Equipos de Climatización. (2017). Qué sabe y qué piensa el sector de la climatización sobre la tecnología Bomba de Calor? Retrieved 14-12-2017 from: http://www.bombadecalor.org/noticias/que-sabe-y-que-piensa-el-sector-de-la-climatizacion-sobre-la-tecnologia-bomba-de-calor

Balaras, C. A., Droutsa, K., Argiriou, A. A., & Asimakopoulos, D. N. (2000). Potential for energy conservation in apartment buildings. Energy and buildings, 31(2), 143-154.

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. Environmental Innovation and Societal Transitions, 16, 51-64.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research policy, 37(3), 407-429.

Bergek, A., & Jacobsson, S. (2003). The emergence of a growth industry: a comparative analysis of the German, Dutch and Swedish wind turbine industries. In Change, transformation and development (pp. 197-227). Physica-Verlag HD.

Bettgenhäuser, K., Offermann, M., Boermans, T., Bosquet, M., Grözinger, J., Manteuffel, B., Surmeli, N. (2013). Heat Pump Implementation Scenarios until 2030: An analysis of the technology's potential in the building sector of Austria, Belgium, Germany, Spain, France, Italy, Sweden and the United Kingdom. Retrieved 14-12-2017 from: http://www.ehpa.org/media/studies-reports/?eID=dam_frontend_push&docID=1204

Boone, J. (2000). Competitive pressure: the effects on investments in product and process innovation. The RAND Journal of Economics, 549-569.

Bryman, A. (2012). Social Research Methods. Oxford University Press.

Bundesamts für Energie. (2015). News aus der Wärmepumpen-Forschung. Retrieved 14-12-2017 from: http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=de&name=de_875018213.pdf

Carlsson, B. (2006). Internationalization of innovation systems: A survey of the literature. Research policy, 35(1), 56-67.

Central Intelligence Agency. (2017). The World Factbook. Retrieved 31-12-2017 from: https://www.cia.gov/library/publications/the-world-factbook/fields/2212.html

Chesbrough, H. (2003). Open innovation. Harvard University Press: Cambride, MA.

Cho, I. Y., Seo, H., Kim, D., & Kim, Y. (2016). Performance comparison between R410A and R32 multi-HPs with a sub-cooler vapor injection in the heating and cooling modes. Energy, 112, 179-187.

Cohen, W. M., Goto, A., Nagata, A., Nelson, R. R., & Walsh, J. P. (2002). R&D spillovers, patents and the incentives to innovate in Japan and the United States. Research policy, 31(8), 1349-1367.

Colaco, A. M. A. P. B. (2015). Assessing the Efficiency of Borehole Heat Exchanger Systems for Acclimatization: Potential in the Portuguese Mainland. Retrieved 14-12-2017 from: https://fenix.tecnico.ulisboa.pt/downloadFile/844820067124881/Thesis_Ana%20Colaco.pdf

Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D, Østergaard, P.A., & Nielsen, S. (2014). Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy, 65, 475-489.

Energy Innovation Austria. (2016). Heat pumps in the energy system of the future: Pioneering technologies and developments from Austria. Retrieved 14-12-2017 from: http://www.energy-innovation-austria.at/wp-content/uploads/2016/06/eia_03_16_E_fin.pdf

Espacenet. (2017). Cooperative Patent Classification. Retrieved 29-11-2017 from: https://nl.espacenet.com/classification?locale=nl_NL#!/CPC=F24D

European Heat Pump Association. (2013). Unleashing the Opportunity: European Best Practice in Building Successful Heat Pump Markets. Retrieved 14-12-2017 from: http://www.ehpa.org/media/studies-reports/?eID=dam_frontend_push&docID=920

European Heat Pump Association. (2014). European HP Market and Statistics Report. Retrieved 10-04-2017 from: http://www.ehpa.org/about/news/article/european-heat-pump-market-and-statistics-report-soonavailable/

European Heat Pump Association. (2016). Sales development by type. Retrieved 8-6-2017 from: http://www.ehpa.org/fileadmin/red/07._Market_Data/2015/Fig_1-1-_Sales_development_by_type.pdf

European Parliament and Council. (2012). Directive 2012/27/EU of the European parliament and of the council of 25 october 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC.

Eurostat. (2017). Electricity Prices Second Half of year 2014-2016. Retrieved 31-12-2017 from: http://ec.europa.eu/eurostat/statistics-explained/images/b/bb/Electricity_prices%2C_second_half_of_year%2C_2014-2016_%28EUR_per_kWh%29_YB17.png

Feng, C., Wang, H., Lu, N., Chen, T., He, H., Lu, Y., & Tu, X. M. (2014). Log-transformation and its implications for data analysis. Shanghai Archives of Psychiatry, 26(2), 105-110.

Ferrari, D. (2009). Introduction to Regression in R Part II: Multivariate Linear Regression. Retrieved 12-6-2017 from: http://scc.stat.ucla.edu/page_attachments/0000/0140/reg_2.pdf

Field, A. (2013). Discovering statistics using IBM SPSS statistics. Sage.

Gaigalis, V., Skema, R., Marcinauskas, K., & Korsakiene, I. (2016). A review on Heat Pumps implementation in Lithuania in compliance with the National Energy Strategy and EU policy. Renewable and Sustainable Energy Reviews, 53, 841-858.

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research policy, 33(6), 897-920.

Guellec, D., Zuniga, M. P., & Martinez, C. (2008). Blocking patents: What they are and what they do. Directorate for Science, Technology and Industry, OECD.

Guoyuan, M., Qinhu, C., & Yi, J. (2003). Experimental investigation of air-source heat pump for cold regions. International Journal of Refrigeration, 26(1), 12-18.

Haupt, R., Kloyer, M., & Lange, M. (2007). Patent indicators for the technology life cycle development. Research Policy, 36(3), 387-398.

Heiskanen, E., & Matschoss, K. (2016). Understanding the uneven diffusion of building-scale renewable energy systems: A review of household, local and country level factors in diverse European countries. Renewable and Sustainable Energy Reviews.

Hekkert, M. P., Suurs, R. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. (2007). Functions of innovation systems: A new approach for analysing technological change. Technological forecasting and social change, 74(4), 413-432.

Hewitt, N. J., Huang, M. J., Anderson, M., & Quinn, M. (2011). Advanced air source heat pumps for UK and European domestic buildings. Applied Thermal Engineering, 31(17), 3713-3719.

Hirth, L. (2013). The market value of variable renewables: The effect of solar wind power variability on their relative price. Energy economics, 38, 218-236.

Hirvonen, J. (2017). The Heat Pump Industry Back on Track towards Growth in Finland. Retrieved 14-12-2017 from: https://www.sulpu.fi/documents/184029/189661/Heat%20Pump%20Industry%20Back%20on%20Track%20towards%20Growth%20in%20Finland%2C%20Press%20Release%201.2017%2Cf.pdf

Hussinger, K. (2006). Is silence golden? Patents versus secrecy at the firm level. Economics of Innovation and New Technology, 15(8), 735-752.

Johnson, A., & Jacobsson, S. (2001). Inducement and blocking mechanisms in the development of a new industry: the case of renewable energy technology in Sweden. Technology and the Market, Demand, Users and Innovation, Edward Elgar, 89-111.

Kanemoto, K., Moran, D., Lenzen, M., & Geschke, A. (2014). International trade undermines national emission reduction targets: New evidence from air pollution. Global Environmental Change, 24, 52-59.

Kemp, R. (1994). Technology and the transition to environmental sustainability: the problem of technological regime shifts. Futures, 26(10), 1023-1046.

Kieft, A. C. (2017). The influence of sectoral context on Technological Innovation Systems: the case of heat pumps in Dutch residential houses. Unpublished manuscript, Utrecht University.

Klevorick, A. K., Levin, R. C., Nelson, R. R., & Winter, S. G. (1995). On the sources and significance of interindustry differences in technological opportunities. Research policy, 24(2), 185-205.

Kuhi-Thalfeldt, R., Lahtvee, V. (2016). Low carbon energy transition in Estonia. Retrieved 14-12-2017 from: http://www.seit.ee/file_dl.php?file_id=505

Laursen, K., & Salter, A. (2006). Open for innovation: the role of openness in explaining innovation performance among UK manufacturing firms. Strategic management journal, 27(2), 131-150.

Levin, R. C., Klevorick, A. K., Nelson, R. R., Winter, S. G., Gilbert, R., & Griliches, Z. (1987). Appropriating the returns from industrial research and development. Brookings papers on economic activity, 1987(3), 783-831.

Litina, E. (2016). How to ‘un-niche’ and ‘coolify’ heat pumps? Retrieved 14-12-2017 from: http://www.ehpa.org/about/media-library/press-releases/?eID=dam_frontend_push&docID=2968

Malerba, F. (2002). Sectoral systems of innovation and production. Research policy, 31(2), 247-264.

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. Research Policy, 41(6), 955-967.

Mayes, A. (2007). HP technology for energy efficient buildings. World Pumps, 2007(491), 22-25.

Ma, G. Y., & Chai, Q. H. (2004). Characteristics of an improved heat-pump cycle for cold regions. Applied Energy, 77(3), 235-247.

Myers, R. H. (1990). Classical and Modern Regression with Application, DUXBURY. Pacific Grove, CA, 93950.

Nille, T. (2015). France: First Heat Pump market in Europe Keys to Success. Retrieved 14-12-2017 from: http://www.ehpa.org/fileadmin/red/_EHPA_Archive_Forum/8th_Heat_Pump_Forum_2015/Presentations/Thierry_Nille.pdf

Patel, P. (1995). Localised production of technology for global markets. Cambridge Journal of Economics, 19(1), 141-153.

Pedersen, E., & Waye, K. P. (2007). Wind turbine noise, annoyance and self-reported health and well-being in different living environments. Occupational and environmental medicine, 64(7), 480-486.

Pesola, A., Hirvonen, J. (2017). The increasing number of heat pumps is not growing the peak power demand in electricity system. Retrieved 14-12-2017 from: https://www.sulpu.fi/documents/184029/0/How%20the%20increasing%20amounts%20of%20heat%20pumps%20influence%20on%20peak%20power%2C%20press%20release-%20Tiedote%20%28ID%2029984%29%2C%20en.pdf

Peter, J. P. (1981). Construct validity: A review of basic issues and marketing practices. Journal of marketing research, 133-145.

Pilkington, A., & Dyerson, R. (2006). Innovation in disruptive regulatory environments: A patent study of electric vehicle technology development. European Journal of Innovation Management, 9(1), 79-91.

Pombo, O., Rivela, B., & Neila, J. (2016). The challenge of sustainable building renovation: assessment of current criteria and future outlook. Journal of Cleaner production, 123, 88-100.

Porter, M. E. (1990). The competitive advantage of nations. Harvard business review, 68(2), 73-93.

Saidur, R., Masjuki, H. H., & Jamaluddin, M. Y. (2007). An application of energy and exergy analysis in residential sector of Malaysia. Energy Policy, 35(2), 1050-1063.

Sandén, B. A., & Hillman, K. M. (2011). A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. Research Policy, 40(3), 403-414.

Singh, H., Muetze, A., & Eames, P. C. (2010). Factors influencing the uptake of HP technology by the UK domestic sector. Renewable energy, 35(4), 873-878.

Smith, A., & Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. Research policy, 41(6), 1025-1036.

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. Journal of evolutionary economics, 1(2), 93-118.

Statistics Solutions. (2017). Kendall's Tau and Spearman's Rank Correlation Coefficient. Retrieved 5-12-2017 from: http://www.statisticssolutions.com/kendalls-tau-and-spearmans-rank-correlation-coefficient/

Sullivan, P. H. (1999). Profiting from intellectual capital. Journal of Knowledge Management, 3(2), 132-143.

Suurs, R. A., & Hekkert, M. P. (2009). Competition between first and second generation technologies: Lessons from the formation of a biofuels innovation system in the Netherlands. Energy, 34(5), 669-679.

Tarnawski, V. R., Leong, W. H., Momose, T., & Hamada, Y. (2009). Analysis of ground source HPs with horizontal ground heat exchangers for northern Japan. Renewable Energy, 34(1), 127-134.

Teece, D. J. (1986). Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. Research policy, 15(6), 285-305.

Teffer, P. (2015). Energy savings label under fire in the Netherlands. Retrieved 14-6-2017 from: https://euobserver.com/beyond-brussels/127943

Truffer, B., & Coenen, L. (2012). Environmental innovation and sustainability transitions in regional studies. Regional Studies, 46(1), 1-21.

Tsoutsos, T., Frantzeskaki, N., & Gekas, V. (2005). Environmental impacts from the solar energy technologies. Energy Policy, 33(3), 289-296.

The World Bank. (2015a). Population density (people per sq. km of land area). Retrieved 11-04-2017 from: http://data.worldbank.org/indicator/EN.POP.DNST?locations=AT-BE-CH-CZ-DE-DK-EE-ES-FI-FR-HU-IE-IT-LT-NL-NO-PL-PT-SE-GB-SK

The World Bank. (2015b). Population, total. Retrieved 10-04-2017 from: http://data.worldbank.org/indicator/SP.POP.TOTL?locations=AT-BE-CH-CZ-DE-DK-EE-ES-FI-FR-HU-IEIT-LT-NL-NO-PL-PT-SE-GB-SK

Ulmanen, J. (2013). Exploring policy protection in biofuel niche development. School of Innovation Sciences. Eindhoven University of Technology, Eindhoven.

Vieira, A. S., Stewart, R. A., & Beal, C. D. (2015). Air source HP water heaters in residential buildings in Australia: Identification of key performance parameters. Energy and buildings, 91, 148-162.

Weatherbase. (2017). Europe. Retrieved 31-12-2017 from: http://www.weatherbase.com/weather/country.php3?r=EUR&regionname=Europe

Wesseling, J. H., Faber, J., & Hekkert, M. P. (2014). How competitive forces sustain electric vehicle development. Technological Forecasting and Social Change, 81, 154-164.

Wesseling, J. H., Niesten, E. M. M. I., Faber, J., & Hekkert, M. P. (2015). Business strategies of incumbents in the market for electric vehicles: Opportunities and incentives for sustainable innovation. Business Strategy and the Environment, 24(6), 518-531.

Wesseling, J. H., & Van der Vooren, A. (2016). Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands. Journal of Cleaner Production.

World Population Review. (2017). Population of Countries in Europe. Retrieved 31-12-2017 from: http://worldpopulationreview.com/countries/countries-in-europe/

World Weather & Climate Information. (2017). Select Your Country of Interest. Retrieved 31-12-2017 from: https://weather-and-climate.com/

Yao, Y., Jiang, Y., Deng, S., & Ma, Z. (2004). A study on the performance of the airside heat exchanger under frosting in an air source HP water heater/chiller unit. International Journal of Heat and Mass Transfer, 47(17), 3745-3756.

Šúri, M., Huld, T. A., & Dunlop, E. D. (2005). PV-GIS: a web-based solar radiation database for the calculation of PV potential in Europe. International Journal of Sustainable Energy, 24(2), 55-67.

Appendix A: Interview Guide

Is it ok with you if I record an audio file of the interview for personal use only?

The research is conducted for my master thesis at Utrecht University where I study Innovation Sciences. The aim of this research is to gain insight into how environmental context conditions are influencing heat pumps. The results are summarized in a report that is presented with respect for the privacy of participants. Data is treated as confidential information.

Concepts:

Development: Technological development such as R&D efforts, patent submissions and technology experiments

Electricity sector: The reliability of the electricity grid in the sense of stability and ability to handle high loads.

Three heat pump variants are included in the research – Air-water, air-air, and ground-water heat pumps. Are you familiar with all these types (explain if not)?

Interview questions

1. What influences heat pump development within your country, all variants included?
    a. How, if so, is this different for heat pump sales?
2. What influences the direction of heat pump development within your country, one variant over another? (e.g. geothermal over air-water)
    a. How, if so, is this different for the direction of heat pump sales?
3. Please explain how important the following factors are for heat pump development and sales including all variants, and explain why:
    a. Temperature
    b. Relative humidity
    c. Population density
    d. Urbanization
    e. The renovation sector
    f. The installation sector
    g. The electricity sector
4. Does your country use energy labels for residential homes?
    a. Can you describe the process by which a house gets an energy label?
    b. What influence does this have on heat pump development and sales including all variants?
    c. What influence does this have on the direction of heat pump development and sales, one variant over another?
5. How would you describe the firm size in the installation sector?
    a. What influence does this have on heat pump development and sales including all variants?
    b. What influence does this have on the direction of heat pump development and sales, one variant over another?
6. What is the average cost of electricity after taxes?
    a. What influence does this have on heat pump development and sales including all variants?

   b. What influence does this have on the direction of heat pump development and sales, one variant over another?

7. Do you have any other questions or comments?

Appendix B: Spearman's Rho results

Table 9 shows the additional results of the Spearman's Rho tests, although these are less suited in a research with relatively small sample sizes.

Table 9. Spearman's Rho

Correlations Spearman's rho		Temp	Rel. humid.	Pop. Dens.	Urban pop.	Elec. price
All variants	Corr. Coefficient	**-.691**	.282	**-.620**	.445	.255
	Sig. (1-tailed)	.009	.201	.021	.085	.225
	N	11	11	11	11	11
Ground-water	Corr. Coefficient	**-.797**	**.425**	-.281	.308	-.097
	Sig. (1-tailed)	0	.027	.108	.087	.338
	N	21	21	21	21	21
Air-water	Corr. Coefficient	**-.546**	.201	-.112	**.478**	.343
	Sig. (1-tailed)	.012	.219	.335	.026	.089
	N	17	17	17	17	17
Air-air	Corr. Coefficient	-.421	.15	**-.615**	.221	.125
	Sig. (1-tailed)	.059	.297	.007	.214	.329
	N	15	15	15	15	15
HP Patents	Corr. Coefficient	**-.503**	.209	-.010	**.466**	.353
	Sig. (1-tailed)	.010	.182	.483	.017	.058
	N	21	21	21	21	21

The Spearman's Rho results for installations of all HP variants (N = 11) shows a significant (p = .009) negative correlation with temperature (coefficient = -.691) and a significant (p = .021) negative correlation with population density (coefficient = -.620).

The Spearman's Rho results for ground-water HP installations (N = 21) shows a significant (p < .001) negative correlation with temperature (coefficient = -.797) and a significant (p = .027) positive correlation with relative humidity (coefficient = 0,425).

The Spearman's Rho results for air-water HP installations (N = 17) shows a significant (p = .012) negative correlation with temperature (coefficient = -.546) and a significant (p = .026) positive correlation with urbanization (coefficient = .478).

The Spearman's Rho results for HP patents (N = 21) shows a significant (p = .010) positive correlation with temperature (coefficient = .374) and a significant (p = .017) positive correlation with urbanization (coefficient = .466).