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The role and potential of hybrid heat pump in an existing Dutch house

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The role and potential of a hybrid heat pump in an existing Dutch house

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Abstract

In the context of the increasing pressure to reach the sustainability targets and the increasing pressure resulting from the Groningen earthquakes, the Dutch government has set targets to significantly decrease the natural gas consumption of the built environment and to transition to a low-carbon heating supply in 2050. Hybrid heat pumps have been voiced as a solution that can decrease the natural gas use of dwellings significantly on a short term, but that can also act as a stepping stone towards a fully renewable heating supply. Hybrid heat pumps are a combination of an air-water heat pump, which should supply the base heating load, and a gas boiler, which supplies the peak heating loads and the domestic hot water.

This study has assessed the potential and role of hybrid heat pump by performing a scenario study and a simulation study, and by combining these in a techno-economic assessment. It has been studied if the hybrid heat pump can lead to a significant reduction of natural gas use, if it can lead to (primary) energy savings, if it can lead to a reduction of CO_2 emissions, and if it can reduce the energy costs of a household. The potential of the hybrid heat pump has been assessed by simulating it in a typical Dutch house. This house is a terraced house built between 1965 and 1974, which is not well insulated and currently heated by a natural gas boiler. Three different insulation levels have been simulated; the current, an improved and a high insulation level. The potential of the hybrid heat pump has been compared to two main competitors; an all-electric air-water heat pump and a gas boiler running on natural gas and/or green gas. Both space heating and the production of domestic hot water have been considered.

The role of the hybrid heat pump has been assessed by constructing four socio-technical scenarios that focus on the transition of the heating system of the studied terraced house, from a natural-gas based system to a system based on renewable energy. The goal of the four scenarios was that the heating system will run completely on renewable energy by 2050, which is concurrent with the targets set by the Dutch national government. The scenarios start in 2018. In two of the scenarios, the hybrid heat pump has an important role in the transition and in the other two, it does not and the main role is taken by one of the two main competitors (i.e., an all-electric air-water heat pump or a gas boiler running on natural and/or green gas).

The results from both the simulation study and the scenario study have been combined in the techno-economic assessment to gain insight on the impacts of the four scenarios on the costs for the home-owner and the CO_2 emissions related to the heating system operating in the studied period.

It was found that the application of a hybrid heat pump can result in a decrease in natural gas use of between 30 and 60 %, depending on the insulation level. However, in terms of the CO_2 emissions and the primary energy use, the hybrid heat pump currently only results in a small decrease compared to the natural gas boiler system. In terms of energy costs, the application of a hybrid heat pump currently results in slightly higher costs. The application of an all-electric air-water heat pump today results in higher costs, CO_2 emissions and primary energy use than a natural gas boiler system.

In the first scenario that resulted from the scenario study, the hybrid heat pump acts as a stepping stone to an all-electric system. This stepping stone role is fulfilled by providing preparation time for grid reinforcements in the electricity grid. The techno-economic analysis also found that the hybrid heat pump acts as a stepping stone by resulting in lower costs for the home-owner when comparing this scenario to one where the home-owner skips the hybrid heat pump and immediately installs an all-electric system in 2025, while resulting in similar CO_2 emissions. This scenario first follows the transformation trajectory by Geels et al. (2016), which leads to the installation of a hybrid heat pump and then switches over to a substitution trajectory when the home-owner installs an all-electric air-water heat pump system.

The second scenario follows the same trajectory as the first but the transformation trajectory continues as the hybrid heat pump gradually switches from natural gas to green gas. In this scenario, the hybrid heat pump acts as an end-solution by decreasing the gas consumption, thus providing an opportunity for the more expensive and less available green gas to be used in the heating and DHW system. It was found that this scenario resulted in the lowest costs for the home-owner over the whole studied period but also in higher CO_2 emissions compared to the first scenario.

In the third scenario, the hybrid heat pump is skipped and a shift is made towards an all-electric air-water heat pump at the first natural switching moment. This involves a more radical change and this scenario follows the technological substitution trajectory of Geels et al. (2016). The third scenario results in the highest costs for the home-owner, but also in the lowest CO_2 emissions, although the difference with the first scenario is small.

In the fourth scenario, no change in the heating system occurs at first, as the gas boiler is renewed at the first natural switching moment. The scenario follows a transformation trajectory as incumbents slowly reorient towards renewable gasses. At the second natural switching moment, in 2040, a decision has to be made on how to change to a renewable heating supply. In the first option the transformation trajectory is continued as the gas boiler is renewed which will run on 100 % green gas in 2050. The second option is to switch to an all-electric system, thus shifting to the trajectory of the third scenario, but much later. It was found that in terms of costs, the first option would be preferred by the home-owner, although the difference was small. Regarding the probability of this scenario it was noted that there is a high uncertainty regarding the supply of green gas available for a large scale use in existing Dutch houses.

When comparing the four scenarios it was found that in all cases, an increased insulation level was key in decreasing costs as well as CO_2 emissions. If adequate insulation was applied in all four scenarios, the costs and CO_2 were roughly similar. It was also found that there is a discrepancy between the preferred height of the insulation level between the policy maker and the home-owner, as more insulation results in lower CO_2 emissions, which is a goal of the policy maker, but also requires significantly higher investments, which is disadvantageous for the home-owner.

Preface

During the interviews for this thesis, in meetings with other people researching this topic, when presenting my work, and in discussions with peers at the university or colleagues at Royal HaskoningDHV, I found that the urgency and the willingness to change the current fossil energy based heating system to a system based on renewable energy is very much alive (although opinions differed on the exact pace at which this transition can occur). It inspired me to see that people working in very different organisations already have reasonably aligned goals and visions when it comes to the 'heat transition'.

However, I have also found that the target to have a low-carbon heating supply for the Dutch built environment in 2050 is a target that will not be met easily. Mainly the question of who should pay the bill that comes with this transition is a difficult one, as we are all starting to realize that this bill will be very large. I very much applaud the mindset of picking up the pace in the transition and to start disconnecting existing houses from the gas grid, but would also like to caution that without thorough and unbiased research, the outcome of these changes might differ from the expectations.

I would like to thank Royal HaskoningDHV for giving me the opportunity to conduct this graduation project in a very professional environment of experts that are both visionaries and realists, which I found to be two very important strengths of the people working there. My supervisor at Royal HaskoningDHV, Edward, always provided supportive feedback when making decisions on the scope of the simulations and was very willing to broaden his focus and to think about the holistic theories that are used in Innovation Sciences and to translate these to real and practical implications. I would like to thank my supervisors at the TU/e, Geert, Jan and Zahra, for the excellent support in guiding this project and for the cooperation between the two departments.

I am grateful to the interviewees and attendees of the expert workshop for their input and interesting discussions. I have met interesting and motivated people with which I hope to work together with in the future. Thank you to Sannah, Jesper and Stef for moderating the group discussions during the workshop.

Lastly, special thanks goes out to my girlfriend Loes and my family for supporting me through the sometimes quite hectic and stressful periods and to my friends Stef and Jesper that were always ready to help in structuring my thesis and to support me throughout this large project.

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Terminology and definitions

ASHP	An air-source heat pump or air-water heat pump
ACH	Air changes per hour
bcm	Billion cubic meters
CBS	Centraal Bureau voor de Statistiek, Statistics Netherlands
Combi-boiler	Gas boiler producing space heat and domestic hot water
COP	Coefficient of performance
CR boiler	A conventional effiency gas boiler
Current insulation	The current insulation level of the studied building
Design option	Sequence of insulation options installed in the scenarios, see Appendix C.2
DHW	Domestic hot water
DSO	Distribution system operator
ECN	Energieonderzoek Centrum Nederland
Heat pump capacity	The thermal capacity of the heat pump at the outside temperature of 2 °C and water temperature of 35 °C (A2/W35)
HHP	A hybrid heat pump
HHV	Higher heating value
High insulation	The high insulation level of the studied building
HR boiler	A high efficiency gas boiler
HR107 boiler	A condensing gas boiler with an efficiency of 107 % when the lower heating value is used
Improved-HT insulation	The improved insulation level of the studied building with high temperature radiators
Improved-LT insulation	The improved insulation level of the studied building with low temperature radiators
LHV	Lower heating value
MLP	Multi-level perspective
Mono-gas	A heating and domestic hot water production system consiting only of a gas boiler
NEV	Nationale energieverkenning
ODE	Opslag duurzame energie
RVO.nl	Rijksdienst voor Ondernemend Nederland, Netherlands Enterprise Agency
S1, S2, S3, S4	Indicators of the four scenarios
S1a, S1b, S1c, etc.	Indicators for the design options in the first scenario
TSO	Transmission system operator
VR boiler	An improved efficiency gas boiler

Chapter 1

Introduction

After the earthquake in January 2018 near Zeerijp, a Dutch town in the province of Groningen, the mining safety authority advised to decrease the production of natural gas from the gas fields in Groningen to 12 billion cubic meters per year, as the gas production was a direct cause of the Zeerijp earthquake, and many other earthquakes. This advice entails decreasing the gas production by almost 50 % from the 2017 level (Staatstoezicht op de Mijnen, 2018).

To ensure security of supply of natural gas, the national gas network operator GTS calculated that, depending on the harshness of the winter, between 14 and 27 billion cubic meters of yearly gas production will be required (Gasunie Transport Services B.V., 2018). However, due to the safety risk for the inhabitants of Groningen, minister Wiebes of economic affairs and climate announced that the Groningen gas production will be decreased to 12 billion cubic meters per year in October 2022 at the latest. The goal is to stop producing natural gas in Groningen in 2030 (Wiebes, 2018a).

In the 2015 United Nations Climate Change agreement, it was agreed by the parties, including the Netherlands, to drastically reduce the emissions of greenhouse gasses (GHG) (UNFCCC, 2015). These GHG emission reduction targets and the fast decreasing production of natural gas in Groningen has led to the Dutch government planning on diminishing the consumption of natural gas and replacing it by renewable sources of energy, as indicated in the 2050 Energy Agenda (Ministry of Economic Affairs, 2016).

Out of the around 35 billion cubic meters (bcm) of gas that was used in 2016 in the Netherlands, around 25 % was used by households (CBS, 2018c). This indicates that these consumers can significantly contribute to the reduction of natural gas use in the Netherlands. Hybrid heat pumps (HHPs) have been presented as a promising technology that will be able to significantly reduce the consumption of gas by these households. A hybrid heat pump system consists of two parts; a heat pump, that supplies the base heating load by using electricity, and a gas-fired boiler, that supplies the heating load in case of peak demand (Näslund, 2013). Proponents of this technology include the CEO of Enexis, one of the Dutch distribution system operators (DSOs) (Grol, 2017) and the consultancy firm Berenschot (Ouden, Graafland, Bianchi, & Friedel, 2017). It has also been advocated as a viable solution by the current minister of economic affairs and climate, Eric Wiebes (Duijnmayer, 2017).

However, the minister also voiced concerns. The hybrid heat pumps are still dependent on natural gas and its infrastructure, thus possibly slowing the transition towards a heating supply based on renewable energy (Duijnmayer, 2017). Furthermore, Eneco and Nuon, both utility companies, introduced hybrid heat pumps in 2016 and 2017 respectively, but these are thus far unsuccessful because they were not able to lead to the expected cost savings[1] (Hylkema, 2017).

Proponents of the hybrid heat pump technology put forward that the hybrid system can be easily installed into existing dwellings, and do not require extensive insulation measures, as all-electric heat pumps do. Therefore, the hybrid heat pump can have a large and positive impact on the transition towards a low-carbon heating supply in the short term (Ouden et al., 2017). In the "Heat Strategy" made by former

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[1] These HHP systems used existing ventilation air as the heat source. The air flow that was expected by the engineers was lower than the actual ventilation air flow in the dwellings. Thus, the ventilation in the houses had to be increased, leading to more incoming cold air, and thus a larger heating demand (Hylkema, 2017).

minister of economic affairs Henk Kamp, the expectation is proclaimed that hybrid heat pumps will supply a considerable amount of heat to existing dwellings (Kamp, 2015). However, the current minister Wiebes voiced concerns about a possible lock-in on the use of gas when applying the hybrid heat pumps on a large scale. A report by Berenschot argues that this is not present, as the use of hybrid heat pumps also leaves the option open for other ways of supplying domestic heat (Duijnmayer, 2017; Ouden et al., 2017).

Foundation “Samen Energie Neutraal” performed calculations on the performance of the hybrid heat pump in different dwellings, and concluded that the hybrid system was the preferred option for all major types of dwellings in the Netherlands (Stokman, 2017). However, it is unsure how these calculations were performed. Fortunately, also some academic work that studies the potential of hybrid heat pumps has been published.

At the 2017 IEA (International Energy Agency) Heat Pump Conference, some early results of the FREEDOM project were presented by Carter and Lancaster (2017). The aim of this project is to improve the control system for hybrid heat pumps (i.e., when should the heat pump work, when should the gas boiler work) via simulations and a field trial, as hybrid heat pumps are not yet widely developed and their impact is not well understood. Particularly the control systems of HHP systems are not yet fully optimised, as argued by Carter and Lancaster (2017). Different operating modes of the hybrid heat pumps and the performance effects of the heat pump capacities have also been studied in the TRNSYS 17 modelling environment by Bagarella, Lazzarin, and Noro (2016a), who report an economic advantage of around 10 %.

In another study, a full-year dynamic simulation was performed of a 1970s’ German single-family home heated by a hybrid heat pump, but with the inclusion of a buffer tank. The used modelling environment for the numerical simulation was Modelica. The study resulted in the buffer tank being not technically and economically justified, as it had a relatively small influence on the performance of the system. Also, the hybrid heat pump system achieved appreciable primary energy savings, thereby justifying future work into these hybrid heating systems in existing buildings (Klein, Huchtemann, & Müller, 2014).

The above-mentioned studies used commercialized hybrid heat pump systems for space heating only. In another study, a hybrid system was designed in a mathematical model, and able to supply space heating as well as domestic water heating. The effect of environmental conditions (e.g., inlet water temperature, ambient temperature) on the performance of the systems was studied. It was found that in a typical Korean house, installing a hybrid heat pump system will lead to an annual energy saving of 4 % (Park, Nam, Jang, & Kim, 2014).

Thus, there are large expectations regarding the potential of the hybrid heat pump for heating Dutch dwellings but there is still some uncertainty regarding the energetic and economic impact of the system. Either way, a heating system that uses hybrid heat pumps (or any other technology than natural gas boilers) on a large scale will look different than the current Dutch heating system. A transition will have to take place to shift from the current system to a new one. In the chapter by Kemp, Rip, and Schot (2001) the path dependency of technological change is highlighted. The existing regime of knowledge, technology and infrastructure determine what steps can be taken at any time. Kemp et al. (2001) call this the shaping of ongoing technological research by an ‘overhang of technological inheritance’. Any transition in the Dutch heating system will also be path dependent.

Academic transition studies have been performed on the Dutch energy sector. For example, Verbong and Geels (2010) applied the transition pathway typology of Geels and Schot (2007) to describe different possible transition pathways of the Dutch electricity system. For possible transition paths of domestic heating systems specifically, no academic papers were found. However, in the Energy Agenda of the Dutch government, a transition path is described for low-temperature heating systems, which applies to dwellings and offices (Ministry of Economic Affairs, 2016).

In the article by Farla, Alkemade, and Suurs (2010), transition paths were studied for the Dutch mobility sector. Especially interesting is the stepping stone technology concept, where the use of hybrid vehicles (i.e., using gasoline and electricity) is viewed as a stepping stone towards all-electric vehicles and where the use of natural gas is viewed as a stepping stone towards a hydrogen economy. A similar stepping stone role can be envisioned for the hybrid heat pump, where it can be either a stepping stone technology towards renewable gas options or all-electric heat pumps. In the article, it is stated that there is a risk of lock-in into these stepping stone technologies, which are not considered desirable end-states (Farla et al., 2010). The use of hybrid heat pumps might also entail a risk of lock-in on the use of natural gas.

Research questions

To sum up, although some research has been done on the performance of the hybrid heat pump in the built environment, no academic research has been performed on the potential of this system in building renovation projects in the Netherlands. Renovation projects are especially interesting because existing buildings involve a greater challenge to transition to a low-carbon heating supply, which is also mentioned in the Energy Agenda (Ministry of Economic Affairs, 2016), and because the potential of the hybrid heat pump lies in the existing buildings (Ouden et al., 2017). Therefore, one part of this research will study the potential of a hybrid heat pump system in renovation projects of a typical Dutch house (i.e., a terraced house built between 1965 and 1974) by performing a simulation. Meanwhile, many expectations of the hybrid heat pumps have been voiced, but uncertainty about the possible role in the transition to a low-carbon heating system in the Netherlands remains. Hence, the other part of this research will study the possible roles of hybrid heat pumps in this transition by exploring different scenarios.

Therefore, the two research questions that will be answered in this research are:

1. *What is the potential of the hybrid heat pump in renovation projects of a typical Dutch house?*
2. *What could be possible roles of the hybrid heat pump in the transition towards a low-carbon heating system for this building?*

The scenario study will provide four different socio-technical scenarios on different roles the hybrid heat pump can fulfil in the transition towards a low-carbon heating system for the studied building. The time period of the scenarios will be from 2018 up to 2050, when the emissions related to the heating of the built environment have to be completely diminished, according to the current cabinet (Wiebes, 2018a). To assess the impact these scenarios have in terms of mainly costs and greenhouse gas emissions, a techno-economic analysis will be performed. This analysis will use the energy consumption data resulting from the simulation study. The simulation study will also provide insight into the change in (primary) energy consumption resulting from a change of heat source or a change in insulation level.

Reading guide

In the next chapter, the theoretical framework will be provided for the scenario study. Chapter 3 will discuss the methods used in the scenario study, simulation study and the techno-economic assessment. The next chapter will focus on the scenario study after which Chapter 5 reports the results from the simulations. The outcomse of both the scenario study and the simulation study are combined in the techno-economic assessment in Chapter 6. The results from the three studies will be linked together in the next Chapter, where the implications for home-owners and policy makers will also be discussed. Chapters 8 and 9 will focus on the conclusion and the discussion of this thesis respectively.

Chapter 2

Theoretical framework

This chapter will introduce the multi-level perspective as a theory and describe the related concepts of landscape, regime and niche levels. Furthermore, it will introduce the concepts of transition pathways and scenarios. These concepts will act as a basis for the scenario study and will therefore be defined here.

2.1 The multi-level perspective

A transition towards a low-carbon domestic heating system in 2050 will not only be limited to a purely technological change, but will also encompass socio-economic change. This transition will likely be a process of socio-technical change, which includes many complex dynamics interacting with each other. Geels (2002) argues that the multi-level perspective (MLP) is a collection of analytical and heuristic concepts to understand these complex dynamics of socio-technical change.

The MLP structures a socio-technical system across three levels in a nested hierarchy, where the upper levels include the lower levels. This can be seen in Figure 2.1. The upper macro-level is called the landscape, the meso-level is called the regime and the lower micro-level is called the niche. These three levels will no be described below, starting with the regime level.

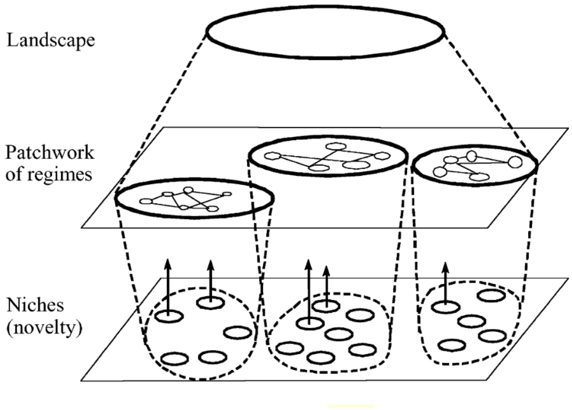

Figure 2.1: Multiple levels of the MLP in a nested hierarchy (Geels, 2002)

2.1.1 The meso-level: regime

At the meso-level of a socio-technical system, the regime exists. Rip and Kemp (1997) describe it in the following way.

> *"A technological regime is the rule-set or grammar embedded in a complex of engineering*

> *practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, and ways of defining problems, all of them embedded in institutions and infrastructures."* Rip and Kemp (1997, p.338)

These rules that coordinate and structure the activities within a regime are differentiated into three dimensions by Geels (2004): regulative rules, normative rules and cognitive rules. Regulative rules refer to explicit, formal rules that guide the behaviour of actors, e.g. economic policies, laws and standards. Normative rules refer to the responsibilities, role expectations, norms and values of actors, formed by interactions within social groups. The last dimension, cognitive rules refers to guiding principles, search heuristics and belief systems. These provide the frames through which meaning of reality is made (Geels, 2004; Geels & Schot, 2007). The continuous reproducing and alignment of these rules by regime actors accounts for the dynamic stability of the existing technological development in the regime, making it difficult for radical innovations to break through in the regime (Bidmon & Knab, 2018; Geels, 2002).

A second source of stability in the regime are the interdependencies between actors and organisations. This can take the form of trust between actors, the organizational structures in large organizations, and market and political power (Geels, 2004). A third source of inertia and stability in a regime are the complementaries between components of a system. This can take the form of sunk investments in infrastructures, adaptations of lifestyle by users, industrial supply chains, economies of scale and the skills of the workforce. The linkages between these components and technologies can result in lock-in. The path dependency that this creates results in incremental innovations that lead to technological trajectories (Geels, 2004). Tensions that arise due to external pressure or internal dynamics can become a threat to the stability of the regime (Geels, 2002).

2.1.2 The micro-level: niche

The dynamic stability and lock-in of the regime provides barriers for radical innovations to develop within the regime. Therefore, temporary protected spaces are created called technological niches. Within these niches, technologies can develop, grow and adapt to the selection environment in the regime (i.e., the market) (Kemp, Schot, & Hoogma, 1998). The degree of stability in the niche level is low, while rules are emerging and developing, in contrast to the well-established rules in the regime (Bidmon & Knab, 2018; Geels & Schot, 2007). Furthermore, actors are entering and leaving continuously while economic structures are not yet developed (Geels & Schot, 2007).

Stability within niches is created by three internal processes: 1. the building of social networks, 2. learning processes to improve the performance of the technology, and 3. the articulation of expectations and visions to guide these learning processes and align the activities of different actors (Bidmon & Knab, 2018; Hoogma, Kemp, Schot, & Truffer, 2002). As the niche-innovation develops, it can eventually break through to the regime, if windows of opportunity have been provided (Geels, 2004).

2.1.3 The macro-level: landscape

Windows of opportunity for niches can be created through external pressure from the socio-technical landscape. Driel and Schot (2005) have identified three kinds of landscape factors: 1. rapid, external shocks (e.g., wars, oil price), 2. long-term changes (e.g., 19^{th} century industrialization), and 3. factors that change only slowly (e.g., climate). These factors are highly varied but have in common that they cannot be influenced by actors in the short run, and therefore the socio-technical landscape is the most stable of all three levels. It is the exogenous context of a socio-technical system that provides structure for interactions of actors (Bidmon & Knab, 2018; Geels, 2002; Geels & Schot, 2007).

2.2 Transitions and pathways

According to the multi-level perspective, transitions take place when developments at all three levels interact and reinforce each other (Verbong & Geels, 2007). Figure 2.2 displays the dynamics of a socio-technical transition according to the MLP. The bottom of the figure displays the internal processes that occur while the niche-technology is developing, (i.e., build-up of internal momentum through learning processes, performance improvements and support from powerful groups), as a response to the problems of the existing regime (Geels, 2002). The top of the figure displays a change in the landscape factors that put pressure on the regime, thus leading to a destabilization of the regime[1] (i.e., depicted by the swarm of small arrows in the middle of the figure). This breaking-up of the regime creates windows of opportunity for the developed niche, which can break through to the regime level (Geels & Schot, 2007). So, Figure 2.2 shows that socio-technical transitions occur when developments at all three levels link up, thus leading to a new regime.

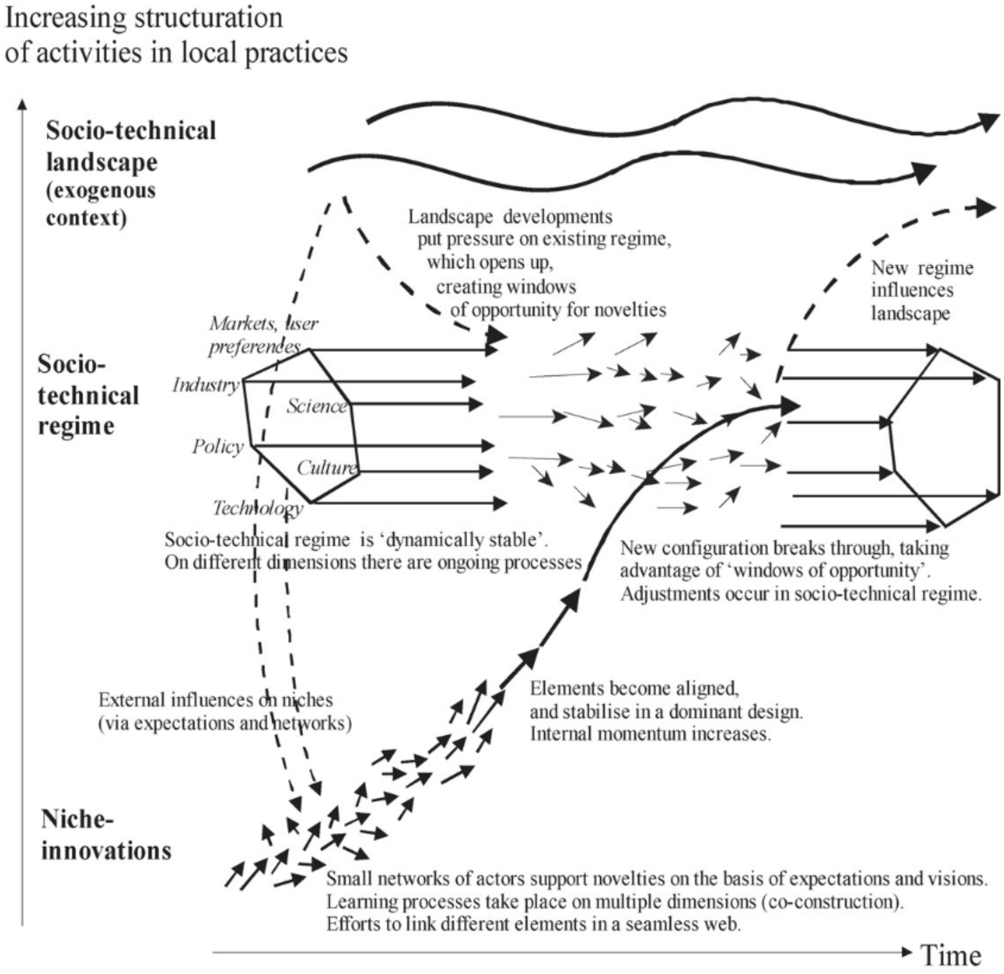

Figure 2.2: Socio-technical transitions in the multi-level perspective (Geels & Schot, 2007)

2.2.1 Typology of socio-technical transition pathways

There are many criticisms on the multi-level perspective described above. One of the main criticisms is that the MLP has a niche-driven bias. Figure 2.2 presumes a strong bottom-up characteristic in the transition, where the niche is the key factor. Geels and Schot (2007) have tried to counter this bias by introducing different transition pathways that aim to diversify in the type of transition.

This typology distinguishes the different transitions by two factors, which are the timing and the nature of the interactions between the levels in the MLP. In the multi-level perspective, emphasis is placed on the aligned timing of landscape pressure with the complete development of a niche. Geels and Schot (2007) differentiate pathways where this timing does not align. They also distinguish pathways where the niche-innovations and landscape developments have reinforcing relationships with the regime, and where they have disruptive relationships with the regime. Landscape developments can have a stabilizing or

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[1] As indicated earlier, the regime can also destabilize by tensions created within the regime (Geels, 2002)

destabilizing effect on the regime while niche-innovations can have competitive or symbiotic relationships with the regime (i.e., replace the regime technology versus being adopted as competence-enhancing add-on to existing regime). Using combinations of these two distinguishing factors, Geels and Schot (2007) have developed a typology of four different pathways of socio-technical transitions.

However, the current study will not directly use the typology by Geels and Schot (2007) but the reformulated typology by Geels et al. (2016). In the reformulated typology, two simplifications have been made. The first is that the scope of the transitions has become more focused on technologies rather than on broader systems. This is beneficial for the current study, as the study is not about a transition of the complete heating system in the Netherlands, but is focused on a specific case with specific technological options. The second simplification is that in terms of the rules described in Section 2.1.1, focus is placed on the regulative rules and less on normative and cognitive rules.

The reformulated typology also includes the possibility of shifts between types of pathways during the transition, which depend less on landscape developments and more on continuous struggles between actors about technology deployment and institutions[2]. These struggles are for example discussions about the effectiveness, costs and desirability of certain technologies, but also about the goals and instruments of policies. They can arise from changing composition and strength of actor coalitions, learning processes, mismatches between expectations and on-the-ground experiences, and landscape developments. Shifts between pathways can also occur due to resistance from incumbents, waves of mobilization and counter-movements. All of these dynamics result in transitions being non-linear, both in progress and direction (Geels et al., 2016).

The four types of pathways made by Geels and Schot (2007) and reformulated by Geels et al. (2016) will be described below. Table 2.2 provides an overview of the typology in terms of actors, technologies, and rules and institutions.

Transformation pathway

In the transformation pathway, a context of moderate landscape pressure, societal debates and tightening institutions, occurring at a moment that niche-innovations have not yet been sufficiently developed, result in the regime gradually reorientating, through adjustments of incumbent actors. This reorientation can occur in different depths, ranging from only changing search routines and standard-operating procedures, to changing the mission and business model of incumbent organizations. Also the change in technology can occur in different depths, ranging from incremental innovations in existing technologies to new and radical innovations. Incumbents therefore do not necessarily remain locked-in to the existing regime in this pathway[3](Geels et al., 2016; Geels & Schot, 2007).

The depth of reorientation and depth of change in technology are associated with different degrees of institutional change. Geels et al. (2016) use concepts from Thelen (2003) to refer to different degrees of institutional change. These concepts are displayed in Table 2.1. According to Geels et al. (2016), incremental technical change is associated with the layering mechanism, while partial and full reorientation processes are associated with the conversion and displacement mechanisms (i.e., higher degrees of institutional change).

Table 2.1: Mechanisms of institutional change by Thelen (2003) as in Geels et al. (2016)

Layering	New institutions are layered on top of existing arrangements without affecting their core logic
Drift	On-the-ground implementation gradually changes policies in use without any official decision
Conversion	The goals of existing policies are adjusted, while instruments remain unchanged
Displacement	New institutions slowly overtake existing ones

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[2] In this context, the term “institutions” does not represent (non-market) organizations, but is similar to the rules introduced in Section 2.1.1.

[3] This is one of the reformulations by Geels et al. (2016). In the original typology by Geels and Schot (2007), incumbents only adopted incremental innovations.

Substitution pathway

The substitution pathway as first described by Geels and Schot (2007) has the largest resemblance with the transition depicted in Figure 2.2. Niche technologies are developed by new entrants and shielded by protective policy, and regime technologies are developed by incumbents. When there is much landscape pressure on the regime at a moment when the niche-innovation is sufficiently developed, the niche breaks through and replaces the existing regime. Geels et al. (2016) further differentiate this pathway by stating that radical innovations are not only developed and deployed by new entrants, but can also be developed by incumbents that diversify from other sectors.

Geels et al. (2016) also identify two patterns for institutional change in the substitution pathway, where they use not only the mechanisms by Thelen (2003), but also the ‘fit-and-conform’ and ‘stretch-and-transform’ concepts by Smith and Raven (2012). The first pattern is associated with the ‘fit-and-conform’ concept, where niche-innovations are developed to fit existing rules and institutions (i.e., limited institutional change, Thelen’s ‘layering’). The second pattern is associated with the ‘stretch-and-transform’ concept, where rules and institutions are adjusted to suit the niche-innovation (i.e., larger institutional change, Thelen’s ‘displacement’).

Reconfiguration pathway

In the reconfiguration pathway, symbiotic niche-innovations are combined with the existing regime to solve local problems. These niche-innovations then create unintended problems and opportunities that trigger a reconfiguration of the system’s components and their relations (i.e., the regime’s architecture), and that trigger innovation cascades as well (Geels et al., 2016; Geels & Schot, 2007).

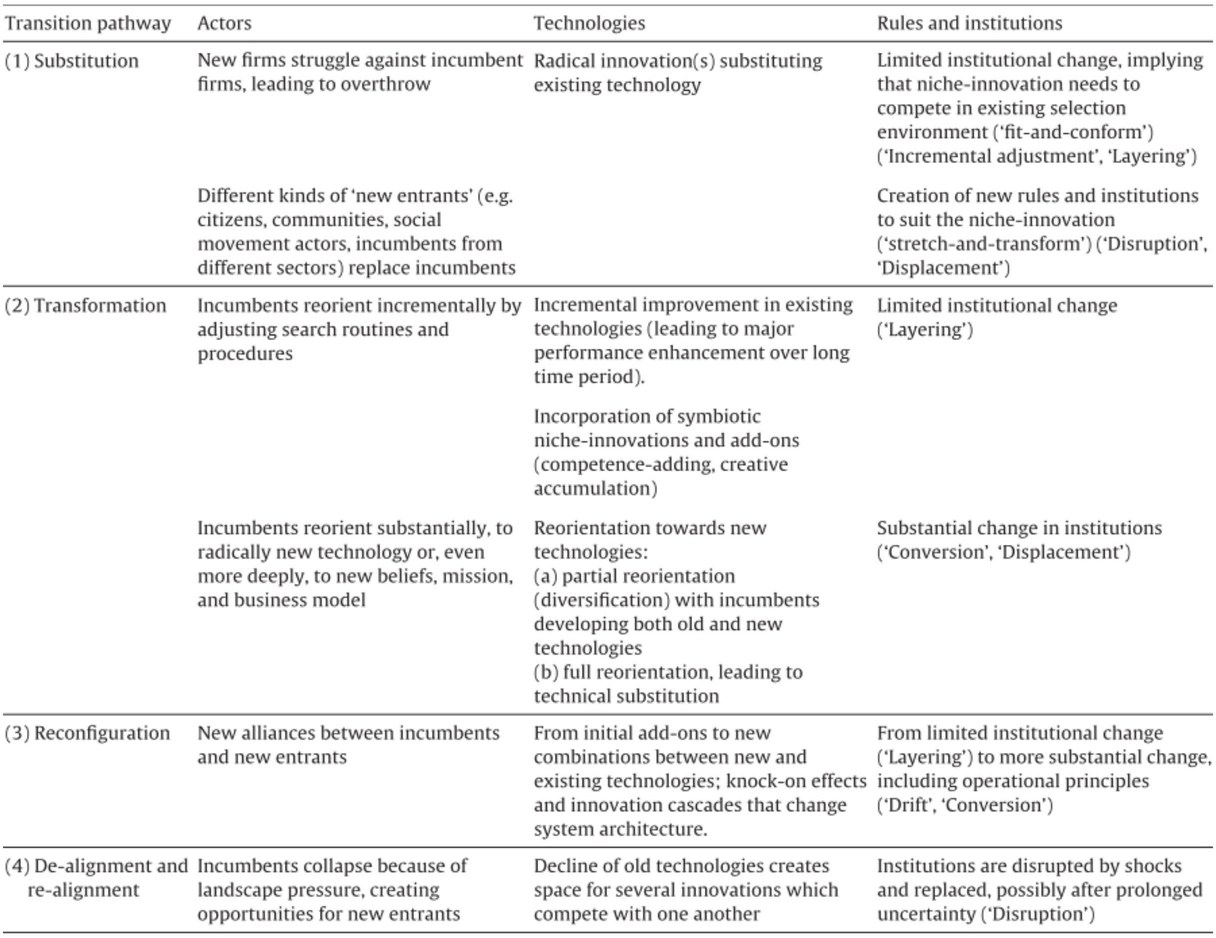
This pathway involves new alliances between incumbents and new entrants and has similarities with the transformation pathway when the first niche-innovation is adopted. In this first stage, limited institutional change is present (i.e., Thelen’s layering). However, the innovation cascade that follows is accompanied by more substantial institutional change (i.e., Thelen’s drift and conversion), which results in an open-ended character of this pathway (Geels et al., 2016).

De-alignment and re-alignment pathway

In the de-alignment and re-alignment pathway, a large and sudden landscape change results in regime actors losing faith in the existing regime. However, no clear substitute for the regime is presented, as niche-innovations are not yet sufficiently developed. Therefore de-alignment occurs, which is that multiple radical niche-innovations emerge that co-exist and compete with each other. Eventually one niche innovation will become dominant, which will lead to re-alignment of a new regime (Geels & Schot, 2007).

In terms of actors, new entrants (part of the niches) and incumbents (part of the regime) are temporally separated. They do not engage in a head-on confrontation because the incumbents have lost faith in the existing regime. In terms of institutional developments, the large landscape shocks will lead to institutional uncertainty as there are no institutional templates available for the situation created in the de-alignment phase. During this phase multiple actor groups (or coalitions) struggle over shaping new institutions, with stability returning when one group prevails (Geels et al., 2016).

Table 2.2: Overview of typology of transition pathways (Geels et al., 2016)



Transition pathway	Actors	Technologies	Rules and institutions
(1) Substitution	New firms struggle against incumbent firms, leading to overthrow	Radical innovation(s) substituting existing technology	Limited institutional change, implying that niche-innovation needs to compete in existing selection environment ('fit-and-conform') ('Incremental adjustment', 'Layering')
	Different kinds of 'new entrants' (e.g. citizens, communities, social movement actors, incumbents from different sectors) replace incumbents		Creation of new rules and institutions to suit the niche-innovation ('stretch-and-transform') ('Disruption', 'Displacement')
(2) Transformation	Incumbents reorient incrementally by adjusting search routines and procedures	Incremental improvement in existing technologies (leading to major performance enhancement over long time period). Incorporation of symbiotic niche-innovations and add-ons (competence-adding, creative accumulation)	Limited institutional change ('Layering')
	Incumbents reorient substantially, to radically new technology or, even more deeply, to new beliefs, mission, and business model	Reorientation towards new technologies: (a) partial reorientation (diversification) with incumbents developing both old and new technologies (b) full reorientation, leading to technical substitution	Substantial change in institutions ('Conversion', 'Displacement')
(3) Reconfiguration	New alliances between incumbents and new entrants	From initial add-ons to new combinations between new and existing technologies; knock-on effects and innovation cascades that change system architecture.	From limited institutional change ('Layering') to more substantial change, including operational principles ('Drift', 'Conversion')
(4) De-alignment and re-alignment	Incumbents collapse because of landscape pressure, creating opportunities for new entrants	Decline of old technologies creates space for several innovations which compete with one another	Institutions are disrupted by shocks and replaced, possibly after prolonged uncertainty ('Disruption')

2.3 Socio-technical scenarios

As has been described above, the multi-level perspective and transition pathways can provide insight in the complex dynamics at work in socio-technical transitions. Hofman and Elzen (2010) present socio-technical scenarios as a complementary tool to help design more robust transition-oriented policies. This 'socio-technical scenarios' method is based upon the MLP to analyse and explain transitions by exploring the way linkages between the different levels of the MLP may set transition paths in motion. These scenarios are not predictions of the future but give insight in the various complex dynamics of driving forces, as well as technological, societal and institutional change, and thus provide a reflexive tool for transition policies (Hofman & Elzen, 2010).

As with the multi-level perspective, socio-technical scenarios do not see technological change as what predominately induces transitions. What induces transitions is the way various actors interact with each other and with technologies, as they develop expectations regarding their potential and the way to realise these (Hofman & Elzen, 2010). These scenarios provide more of a qualitative storyline rather than a linear technological diffusion story by adhering to the following characteristics: 1. the co-evolution of technology and its social embedding is described (i.e., socio-technical development is shown), 2. learning processes and niche dynamics should be apparent, 3. attention is paid to the development of innovations and the interaction between niches (i.e., not only diffusion of individual innovations is described), 4. niche-accumulation is addressed (i.e., the development of innovation through successive niches) (Hofman & Elzen, 2010; Hofman, Elzen, & Geels, 2004).

The socio-technical scenario method by Hofman and Elzen (2010) uses the typology of Geels and Schot (2007) to provide the initial building blocks for the construction of the scenarios. The exact methodological steps proposed by Hofman and Elzen (2010) will be addressed in Section 3.2.1.

Chapter 3

Methods

This study will consist of three main parts, a scenario study, a simulation study and a techno-economic analysis. In this chapter the methods used for these parts will be described. The study will focus on one building case that is representative for a large dwelling stock in the Netherlands. This case will be described first, after which the methodological steps for the scenario study will be explained. In the third section, the simulation methods will be described and the techno-economic analysis will be dealt with lastly.

3.1 The case study

The Dutch heating system is a large and complex system that cannot be studied entirely. Therefore, one case study will be examined towards the context where the potential of the hybrid heat pump lies. This context is existing buildings with low/moderate insulation levels and a high temperature heating system with radiators which are currently heated by a gas boiler. This type of heating system is common in the Netherlands, and is less directly suitable for heating with all-electric heat pumps.

The Netherlands Enterprise Agency (i.e., Rijksdienst voor Ondernemend Nederland, RVO.nl) publishes example cases of houses that represent the dwelling stock in the Netherlands. The terraced house 1965-1974 fits the heating system described above and represents a large share of the Dutch dwelling stock, and will therefore be chosen as a case. Out of the 606,000 buildings of this type, 47 % is privately owned and the same share is owned by social housing agencies (Agentschap NL, 2011). For this research, the scenarios will be written mainly from the perspective of a home owner. More information on the building construction can be found in Section 3.3.1.

3.2 Scenario study methods

The methodology of the scenario study is based on the seven methodological steps of the socio-technical scenario (STSc) method of Hofman and Elzen (2010). As has been described in Chapter 2, these methodological steps use the multi-level perspective as the theoretical framework. In the current study, the different levels of this perspective can be defined as followed. At the meso/regime level, the socio-technical system under study is the heating and DHW system used in the studied building case. At the micro/niche level, the focus will be on the hybrid heat pump and two of its direct competitors: an all-electric air-water heat pump and renewable gas. The complementary niche of extra insulation measures will also be considered. At the macro/landscape level, the sociotechnical landscape influencing the other levels will be studied (e.g., sustainability discourse, gas production in Groningen).

3.2.1 Seven methodological steps towards scenarios

As indicated above, these seven methodological steps have been based on the methodology in Hofman and Elzen (2010).

Step 1: Specification of objectives
The main users and main functions of the scenarios are identified, as well as the domain and time period in which the scenarios take place. The goal and the objectives of the scenarios are explained and the relevance of these objectives are presented as well.

Step 2: Analysis of recent and ongoing dynamics
The developments and interactions within the landscape, regime and niche levels are studied in this step. The goal of this dynamics analysis is to find the starting points of change that can lead to different transition paths.

For the analyses of the dynamics on the landscape, regime and niche levels, the studied factors of Elzen, Geels, and Hofman (2002) will be used. For the socio-technical landscape, these factors are for example sustainability dimensions, political factors, and natural factors. For the socio-technical regime, these factors are the consumption of heat in the built environment, the key stakeholders and system set-up and policies. Lastly, for the niche analysis the studied factors are for example the niche characteristics, expectations and momentum, regime mismatch and barriers to further adoption.

Step 3: Inventory of potential linkages
Here the possible linkages between the dynamics in the three levels are analysed, as these linkage opportunities can play a role in the transition paths. To characterize the linkages, 'typical' patterns in transition literature are taken into account. For example, stepping stone technologies (Farla et al., 2010), path dependency (Kemp et al., 2001) and hybridization (Elzen et al., 2002).

Step 4: Design choices
In this step specific choices have to be made regarding the number and the nature of the scenarios: what niches are considered and what is the role of the landscape effects in each scenario? The goal here is to work out the end-state of the scenarios and to develop the basic pathways that lead to these end-states, by making a schematic with the main characteristics of each scenario. To provide the scope of the simulation method section (Section 3.3) and the techno-economic analysis method section (Section 3.5), a brief outlook into the results of step 4 is given in the box on the next page.

Especially important here is the influence of the landscape effects on the different scenarios. As Elzen et al. (2002) indicate, scenario studies often have a 'macro-bias', where the macro-aspects dictate the processes and actions on the meso and micro level (i.e., a top-down approach). These aspects, such as economic growth then dominate the outcome of the scenarios. To circumvent this bias, the same landscape effects are used in all scenarios, but they are translated differently into institutional frameworks and regimes in the socio-technical systems of each scenario (Elzen & Hofman, 2007).

Step 5: Develop scenario architectures
The main characteristics of the previous step are further specified in terms of the main driving forces, actor networks, rules and institutions, and technology developments. The sequence of linkages between and within the three levels are specified. And as these linkages shape major changes in the socio-technical system, the pathways are sketched towards the end-states defined in step 4. The typology of socio-technical transition pathways of Geels et al. (2016) is used as a basic structure of the architecture of the scenarios.

Step 6: Elaborate all scenarios
The last step of producing the transition paths is to elaborate the paths in detail. The scenarios will be structured in different phases around the lifetime of the heat source.

Step 7: Reflection and recommendation
After producing the transition paths, the scenarios should be evaluated and reflected on the background and the objectives set at Step 1. Recommendations are developed and attention is paid on why the scenarios have contrasting paths and outcomes. The recommendations will be mainly dealt with in Chapter 7.

Outlook for step 4
Figure 3.1 depicts the four scenarios considered in this study. The heat sources in 2018 (current), 2030 (intermediate) and 2050 (end-state) are displayed. These can either be a natural gas boiler, a hybrid heat pump, an all-electric air-water heat pump, or a renewable gas boiler (i.e., indicated by the leaf). The natural switching moments are in 2025 and 2040.

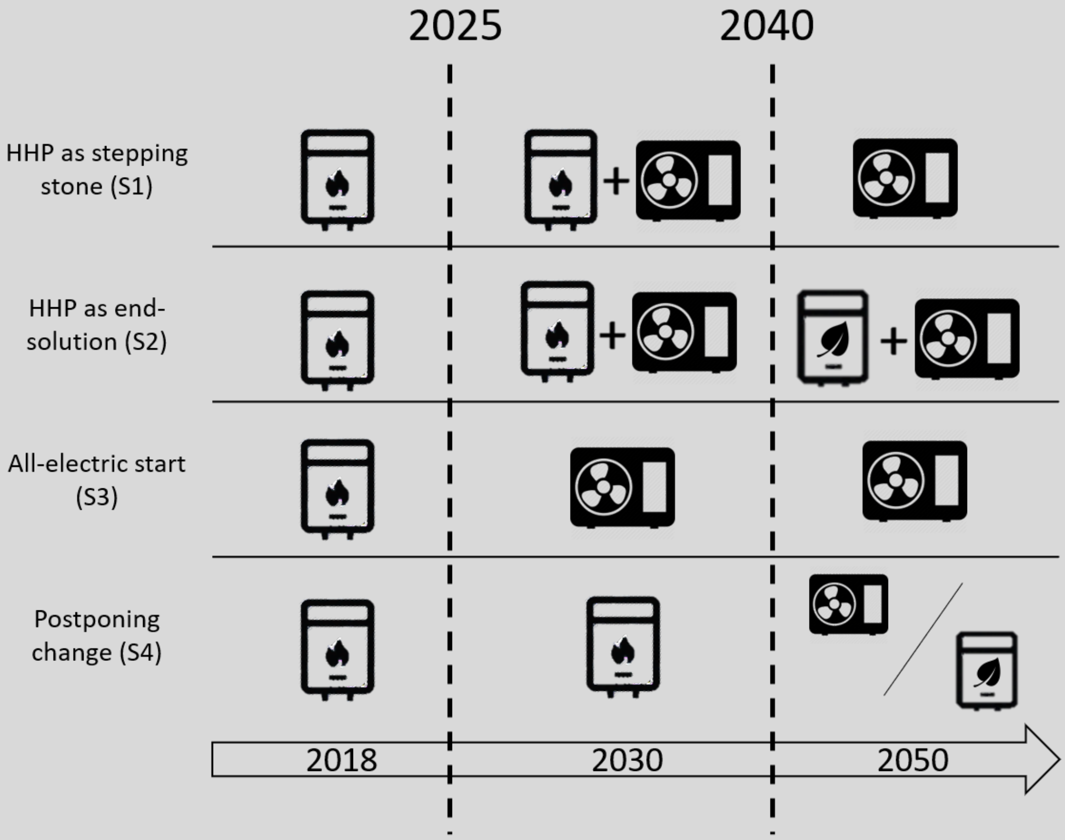


Figure 3.1: The four considered scenarios with the associated heat sources

3.2.2 Data gathering and process

In the scenario study, five different data sources are used: academic literature, grey literature, media sources, expert interviews and an expert workshop. In step 1, Dutch policy documents containing sustainable energy targets, e.g. Ministry of Economic Affairs (2016); Rutte, van Haersma Buma, Pechtold, and Segers (2017), and reports from research and consultancy firms, e.g. Ouden et al. (2017); Schepers, Naber, Rooijers, and Leguijt (2015), will be used. In step 2, next to grey literature, also academic literature, e.g. Carter and Lancaster (2017); Elzen et al. (2002); Klein et al. (2014), media sources, e.g. Duijnmayer (2017); Grol (2017), and expert interviews will be used. In step 3, academic literature, such as cited in the previous section, will be the main data source.

As step 4 mainly entails design choices made by the researcher, no external data sources will be used here. In step 5, experts will be interviewed as input for the scenario architectures. The scenarios made in step 6 will be reviewed by organizing an expert workshop. In step 7, the produced scenarios will be reflected upon by making use of the grey literature used in step 1. The interviewee list can be found in Appendix E.1. The list of attendees at the expert workshop can be found in Appendix E.2.

3.3 Simulation study methods

A simulation study is conducted in TRNSYS, a transient systems simulation program. In this section the general set-up, physical assumptions and main parameters of the model will be explained. Please refer to Appendix B for details on the implementation in TRNSYS.

In Figure 3.1 the four scenarios and their corresponding heat technologies were displayed. These technologies will be studied in the simulations. As the insulation level of the building and the temperature level of the heat emission system could have a large effect on the performance of the heating system, different insulation levels and heat emitters are simulated. These are described in Section 3.3.1. By adding the different possible insulation levels and heat emissions systems to the scenarios displayed in Figure 3.1, a total of eighteen building and heating options can be studied. Appendix A.1 shows which eleven options were simulated and which seven were not.

The potential of the heating systems will be assessed on multiple factors. First, the primary energy consumption is calculated to assess the dependency on fossil energy resources. Second, the gas use itself is another important factor, especially with the known challenge coming from the decreasing production of natural gas in the Netherlands. Third, the climate impact of the system can be assessed by calculating the amount of CO_2 emitted by the system. Fourth, the fraction of the amount of heat delivered by the heat pump, compared to the total amount of delivered heat will be assessed with the load factor. The potential of the hybrid heat pump system increases with the increasing relative use of the heat pump. Fifth, the operating performance of the heat pump will be assessed by the seasonal performance factor. This assessment will be part of the techno-economic assessment that is explained in Section 3.4.

In the simulation, the building with its corresponding heating profile will demand a certain heating load at each time step over a year, which should be supplied by the heat producing system. The set-up of the building model will be explained first, after which the set-up of the heat sources will be dealt with.

3.3.1 Building and household set-up

The building set-up consists of the building construction, the user profiles and gains, temperature control and the central heating system, which will be explained in that order. As has been stated earlier, Appendix B describes the implementation of the physical assumptions and used parameters in the TRNSYS model.

Building construction

As described in Section 3.1, the studied building has been based on one of the example buildings by Agentschap NL (2011); the terraced house built between 1965-1974. This building was chosen because it represents a large share of the Dutch building stock, because it is heated by a natural gas boiler with high temperature radiators and because it has natural ventilation. The floor plans of the building can be found in Appendix A.3.

Table 3.1 displays the main building construction parameters for the three considered insulation levels. The current and improved insulation levels correspond to those from the example building (Agentschap NL, 2011). The high insulation level parameters were based on the common practices on the website of Milieu Centraal (n.d.-e). In the current insulation level, the only insulation measures are the double glazed windows. There is however, still some window surface that is single glazed. In the improved insulation case, the glass type is changed to HR++ glazing, cavity wall insulation is added, as well as floor and roof insulation. In the high insulation case, the glass type is changed to triple glazing, outer façade insulation is applied, as well as floor and roof insulation. It has to be noted that the three considered insulation levels do not cover the whole field of insulation options, but are chosen in such a way to give insight on how different insulation levels impact the energy performance of the studied heat sources.

It can be seen in the table that the adjacent walls between the studied house and the neighbouring terraced houses are assumed to be adiabatic, i.e. no heat is transferred through these walls. As the example building does not include any specification regarding the infiltration rate, values are taken from van Gemen, Sijpheer, Roossien, and Opstelten (2016) and cross-checked with ECN, TU Delft, TNO, and DHV (2009). In these documents, qv;10 infiltration rates are given for different construction years. For the current insulation level, the value for 1970 is taken and for the improved and high insulation levels, the value for a building built after 2010. Because these infiltration rates are given in the qv;10 value, and TRNSYS requires ACH values, the infiltration rates have to be converted. Appendix A.2 explains how this is done.

Table 3.1: Building construction parameters

		Current insulation	Improved insulation	High insulation
Usable floor area	$[m^2]$	104	104	104
Window glass type	[-]	Single glazing & double glazing	HR++ glazing	Triple glazing
Window surface	$[m^2]$	4.3 & 21.3	25.6	25.6
Heat transfer coefficient of windows	$[W/m^2 \cdot K]$	5.2 & 2.9	1.80	1.30
Thermal resistance of floor	$[m^2 \cdot K/W]$	0.17	2.53	2.53
Thermal resistance of outer façades	$[m^2 \cdot K/W]$	0.43	2.53	4.00
Thermal resistance of roof	$[m^2 \cdot K/W]$	0.86	2.53	4.00
Thermal resistance of adjacent walls	$[m^2 \cdot K/W]$	Adiabatic	Adiabatic	Adiabatic
Infiltration rate	$[dm^3/s \cdot m^2]$	3.5	1.25	1.25
Orientation	[-]	North-south	North-south	North-south

User profiles and gains

The occupancy schedule for working families from Hamdy, Carlucci, Hoes, and Hensen (2017) is used in this study. The living area (i.e., the ground floor) is assumed to be occupied from 07:00 to 08:00 and from 18:00 to 23:00 during weekdays and from 07:00 to 23:00 during weekends. The sleeping area (i.e., the first floor) is assumed to be occupied from 23:00 to 07:00 each day.

For the domestic hot water profile a daily demand of 40.29 L per person at 60 °C is assumed based on Normcommissie "Energieprestatie van gebouwen" (2012). The profile has been simplified to the extreme case of each person using this amount of water completely in one instance per day, when taking a shower. This is done because supplying a high power is key when assessing DHW production. If a more spread-out profile had been used, the DHW production source will not be tested at maximum load. The shower uses 8 litres of water per minute (Foekema & van Thiel, 2011). For each occupant, this accounts for 5 minutes of showering each day. Two of the occupants use the shower in the morning, while one occupant uses the shower in the evening.

The internal heat gains from lighting and equipment is assumed to be 2.4 W/m^2, based on Hoes, Trcka, Hensen, and Bonnema (2011) and Plas (2017). 20 % of this account for lighting and 80 % for electrical equipment. For the internal heat gains from people, the 130 W person from ASHRAE (2013) is used. This corresponds to one person doing light work. The building is occupied by three people (Agentschap NL, 2011), and for both heated areas, the heat gains are only on when that area is occupied. More details can be found in Appendix A.4.

Temperature control and ventilation

The temperature is controlled by a thermostat on the ground floor. The heating schedule follows the occupancy profile of the living area but starts one hour before the area is occupied (i.e., at 06:00 and at 17:00). When occupied the heating setpoint is 22 °C, when not occupied, the setpoint is 18 °C. No active cooling system is assumed in the studied case.

Next to the infiltration rate, there is also outside air entering the building through natural ventilation, which is set to 0.2 ACH for all insulation levels, based on van Gemen et al. (2016). In case of overheating, ventilation cooling is applied by the opening of windows. The ventilative cooling strategy has been based on the work of Hamdy et al. (2017) and is explained in more detail in Appendix A.5.

Central heating system

Figure 3.2 displays the set-up of the central heating system with a gas boiler as the heat source. In this section, the focus will be on just the central heating system. After the heat source, the hot water flow is split over two radiators, one for each heated area (i.e., ground and first floor). After the radiators have transferred the heat from the hot water to the rooms, the cold water flow returns to the heat source. The 50 W circulation pump is located upstream of the heat source.

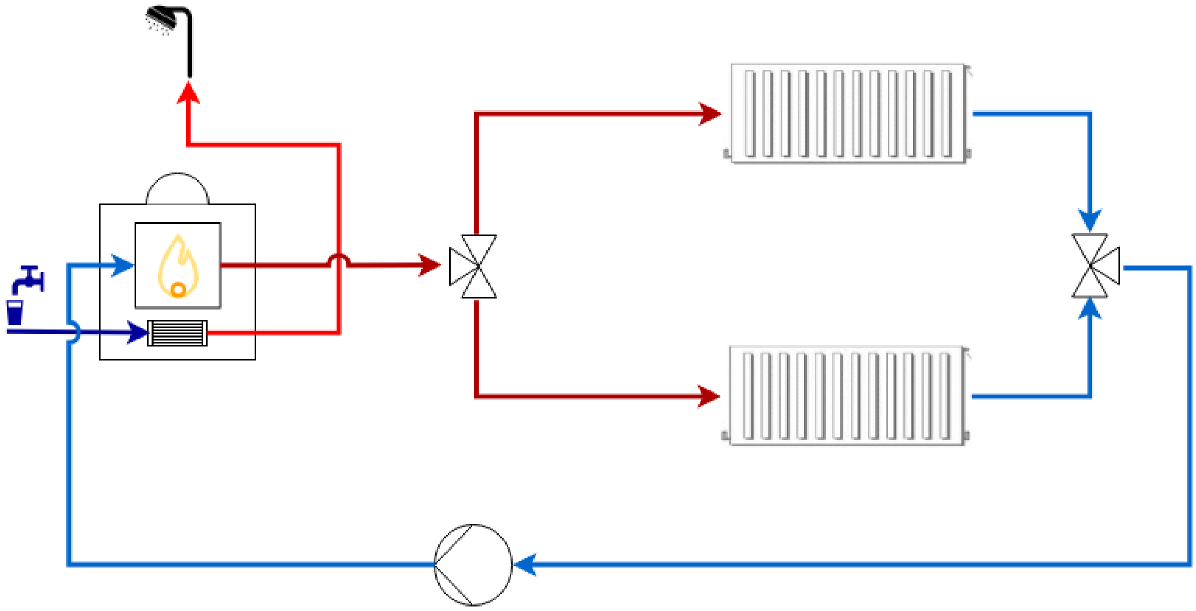


Figure 3.2: Schematic displaying the central heating system with a heat source, the radiators and a pump. The production of DHW is displayed as well.

The pump is assumed to operate at 100 % efficiency, meaning that no heat is transferred from the pump to the water flow. The electricity use of the pump is not taken into account when calculating the energy used by the heating system, as it is present in all studied cases and uses only about 90 kWh per year (Grundfos, 2014).

40 % of the flow coming from the heat source is send to the radiator on the first floor and 60 % is send to the radiator on the ground floor. To calculate the required capacity for the radiators, rules of thumb from Prolix (n.d.) were used. For a building built before 1990, a living room with two outer walls requires 70 W/m^3 and a bedroom with two outer walls requires 60 W/m^3 of radiator capacity. This corresponds to a radiator capacity of 10.4 and 9.9 kW for the living and sleeping areas respectively with a supply temperature of 75 °C and a room temperature of 20 °C.

The radiators described above are the original high-temperature radiators of the building. However, in some of the studied (hybrid) heat pump models, the high-temperature (HT) radiators are replaced by low-temperature radiators. The capacity of these radiators is equal to the capacity of the HT-radiators, with one key difference; the designed supply temperature of the LT-radiators is 55 °C.

3.3.2 The studied heat sources

The heat sources that are considered in this study are a gas boiler, an air-source heat pump, and a hybrid heat pump (i.e., a combination of the previous two heat sources). Refer to Appendix B for more details on the implementations of the assumptions and parameters described below in the TRNSYS model.

Gas boiler

For all three insulation levels, the capacity of the gas boiler is 19.5 kW. There are two main reasons why the capacity remains equal with increased insulation. First, 19.5 kW is already at the lower end of the range of possible capacities on the Dutch market. Second, as insulation increases, the maximum required capacity is no longer governed by the space heating demand but by the DHW demand, which is equal in all cases. The chosen gas boiler has a ‘CW3 gaskeur’ certificate, which is currently the lowest class available. However, this is adequate for an average use of DHW (Consumentenbond, n.d.-a).

The studied gas boiler is an ‘HR107’ condensing gas boiler. By using the latent heat in the flue gasses, the efficiency is improved. HR107 means that the efficiency is 107 %, however this is when the lower heating value (LHV) of natural gas is used (i.e., which does not include the latent heat of the water vapour). When the higher heating value (HHV) is used (i.e., which does include the latent heat of the water vapour), the efficiency is 96 %. The efficiency of DHW production is 82 %, according to the Gaskeur certificate by Meekma (2015) for the Remeha Tzerra M 24c Plus (Remeha, n.d.).

As explained in Section 3.3.1, the heating setpoint when occupied is 22 °C and when not-occupied 18 °C. The heating power of the gas boiler is modulated by a PID-controller, which tries to minimize the error between the desired setpoint temperature and the room temperature with a control loop feedback mechanism (see Appendix B.6). DHW production always has priority over space heating demand. Therefore, the gas boiler produces heat for solely the DHW when there is DHW demand.

All-electric air-water heat pump

To decide on the required capacity of the heat pump, several heat pump capacities are tested for each studied insulation level. The criteria for choosing the capacity is as follows: choose the lowest heat pump capacity that heats the building adequately. Adequate heating of the building is represented by two indicators called ‘f-factors’. The first f-factor, $f_{underheat}$, indicates the amount of times the building was underheated, i.e., when the room temperature was below the setpoint temperature minus a bandwidth. The second f-factor, $f_{bandwidth}$, indicates the amount of times the room temperature was not within a bandwidth around the setpoint temperature, i.e., this factor also includes overheating. They are defined as follows.

$$f_{underheat} = \frac{N_{underheat}}{N_{total}}$$

$$N_{underheat} \ \text{ counted if } \ T_{room} < T_{setpoint} - \frac{\delta T_{bandwidth}}{2}$$

$$f_{bandwidth} = \frac{N_{bandwidth}}{N_{total}}$$

$$N_{bandwidth} \ \text{ counted } \begin{cases} \text{if } T_{room} < T_{setpoint} - \frac{\delta T_{bandwidth}}{2} \\ \text{or if } T_{room} > T_{setpoint} - \frac{\delta T_{bandwidth}}{2} \end{cases}$$

$$T_{bandwidth} = 2\,^{\circ}\mathrm{C}$$

With $N_{underheat}$ indicating the amount of time steps the room temperature on the ground floor, T_{room} (i.e., where the thermostat is located), is lower than the setpoint temperature $T_{setpoint}$ minus half a bandwidth $\delta T_{bandwidth}$. $N_{bandwidth}$ indicates the amount of times the room temperature is below the setpoint temperature plus or minus the bandwidth. The total amount of time steps of the yearly simulation is indicated by N_{total}.

The building with the air-source heat pump is heated adequately if the f-factors for the air-source heat pump (ASHP) case are not significantly higher ($\alpha = 0.05$) than that of the gas boiler case with the same insulation level ($f_{ASHP} < (1 + \alpha) \cdot f_{gas}$). For all studied heat pump capacities, both f-factors are calculated. From the capacities that met the criteria above, the lowest is chosen. The studied thermal capacities of the heat pump range from 3 to 10 kW.

The ASHP also produced DHW by using a storage tank with a heat exchanger coil and an auxiliary electrical heater. This set-up was based on the Techneco Loria Duo heat pump system. The volume of the tank is 181 litres and the auxiliary heater has a thermal capacity of 1.6 kW. More information can be found in Appendix B.9.

The heating setpoints are equal to the gas boiler case. However, the heat pump does not use a PID controller but oscillates the room temperature within a bandwidth of 1 °C around the setpoint temperature.

Hybrid heat pump

In the current market, hybrid heat pump systems are available where the heat pump and gas boiler are installed in parallel as well as in series[1]. Because using a parallel system adds extra complexity to the model, due to the extra variable of the ratio of flow rate through both devices, this study uses a series set-up of the hybrid heat pump system, with the heat pump located upstream of the gas boiler.

The capacity of the gas boiler in the hybrid heat pump is equal to the capacity of the gas boiler in the case where solely the gas boiler is used, as the gas boiler should be able to cover the peak heating demand as well as the DHW demand, which both do not change in comparison to the mono-gas boiler model. With regards to choosing the capacity of the heat pump, the same criteria for adequate heating is used as with the all-electric system ($f_{HHP} < (1 + \alpha) \cdot f_{gas}$). However, due to the bivalent operation of the hybrid heat pump, another varying factor is added, which is the operation mode of the system. As explained in the box on the next page , the HHP can operate in a bivalent alternative mode or in a bivalent parallel mode, which is the first extra varying factor. The second and third extra varying factors are the temperatures at which the heat pump and the gas boiler turn off or on (i.e., T_{biv} and $T_{cut\text{-}off}$).

A method has been developed to determine the capacity and operation strategy of the hybrid heat pump, for each insulation level. First, the alternative bivalent operation strategy is tested, where either the heat pump or the gas boiler is providing space heating, depending on the outside temperature. The method consists of two steps, which are depicted in an example case in Figure 3.4. For each heat pump capacity, ranging from 1 to 8 kW, different switching temperatures were tested (i.e., $T_{cut\text{-}off}$, which is the same as T_{biv} in the alternative bivalent operation strategy), ranging from −12 °C to 14 °C with 2 degree intervals. For each combination of heat pump capacity and switching temperature, the f-factors and the total primary energy consumption are calculated[3]. The concept of primary energy is used to provide insight into the (fossil) energy consumption of the tested system, by producing one number that takes into account both energy sources (i.e., electricity for the heat pump and natural gas for the gas boiler). In the first step of the developed method, the studied systems that did not adequately heat the building are dropped (i.e., where $f_{HHP} > (1 + \alpha) \cdot f_{gas}$). In the second step, the system is chosen that results in the lowest primary energy consumption. This way, the system is chosen that provides adequate heating with the lowest primary energy consumption. The two steps are depicted in Figure 3.4 by the numbered arrows.

The method to determine the operation strategy and heat pump capacity for the hybrid heat pump operating in parallel bivalent operation is similar to the method for alternative bivalent operation, with one extra variable. As explained in the box on the next page , the parallel bivalent operation uses two switching temperatures. If the outside temperature is higher than $T_{cut\text{-}off}$, the heat pump switches on. Up until T_{biv}, the heat pump and gas boiler are operating in parallel. When the outside temperature rises above T_{biv}, the gas boiler is switched off.

In the parallel bivalent case, for each heat pump capacity, T_{biv} is equal to the switching temperature used in the respective alternative bivalent operation case, where in both cases the heat pump should be able to solely provide the heat demanded by the space heating system. With T_{biv} known for each heat pump capacity in the parallel bivalent operation scheme, the $T_{cut\text{-}off}$ is varied in three or four steps of −4 °C (e.g., if the T_{biv} was 4 °C, the tested $T_{cut\text{-}off}$ were 0 °C, −4 °C and −8 °C). The reason why $T_{cut\text{-}off}$ is found by trial-and-error and not through the calculations explained in the box above, is that it is not possible to produce the graph of the thermal capacity of the heat pump for different outside temperatures (i.e., the blue line in Figure 3.3). The main reason why this is not possible is because the datafile that the heat pump component in the model is using, was made by testing the heat pump under standardized conditions (EN 14511), which is not completely realistic (e.g., the temperature difference of the water entering and exiting the heat pump is only 5 °C (EHPA & VDE, 2015; Mitsubishi Electric, 2015)).

The next steps in deciding on the system sizing for the parallel bivalent operation mode are similar to the method used in the alternative bivalent mode, where first the f-factor criteria is applied, after which the heat pump capacity and operation temperatures are chosen which uses the lowest amount of primary

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[1] For example, the Remeha Tzerra HP 40-5c has the heat pump placed in series and upstream of the gas boiler while it is preferred to install the Techneco Elga heat pump in parallel with the gas boiler.

[2] When the heat pump operates at a COP of 2.1, 1 kWh of heat produced by the heat pump will have used the same amount of primary energy as 1 kWh of heat produced by the heat pump: $\frac{Q_{boiler}}{\eta_{boiler}} \cdot PEF_{gas} = \frac{Q_{HP}}{COP} \cdot PEF_{electricity}$.

[3] The used primary energy factors are described in Section 3.4.

Bivalent operation modes

A hybrid heat pump can operate in two modes: the bivalent alternative operation mode and the bivalent parallel operation mode. Figure 3.3 depicts both modes. The orange line displays the building heat load, which decreases with ambient temperature (displayed on the x-axes). The blue line depicts the thermal capacity of the air-water heat pump in the HHP system, which increases with increasing ambient temperature. The temperature at which these two lines intersect is called the bivalent temperature (T_{biv}). At this outside temperature, the heat pump is able to exactly supply the heat load demanded by the building. The differing factor between the two operation modes is the temperature at which the heat pump of the hybrid heat pump system is switched off ($T_{cut\text{-}off}$).

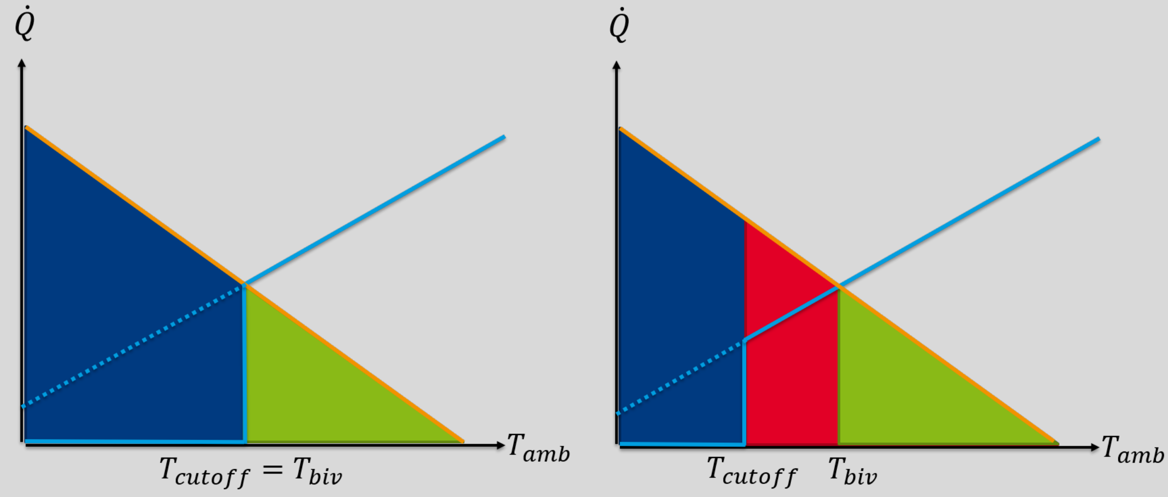


Figure 3.3: The two operation modes of the HHP: bivalent alternative operation (left) and bivalent parallel operation (right)

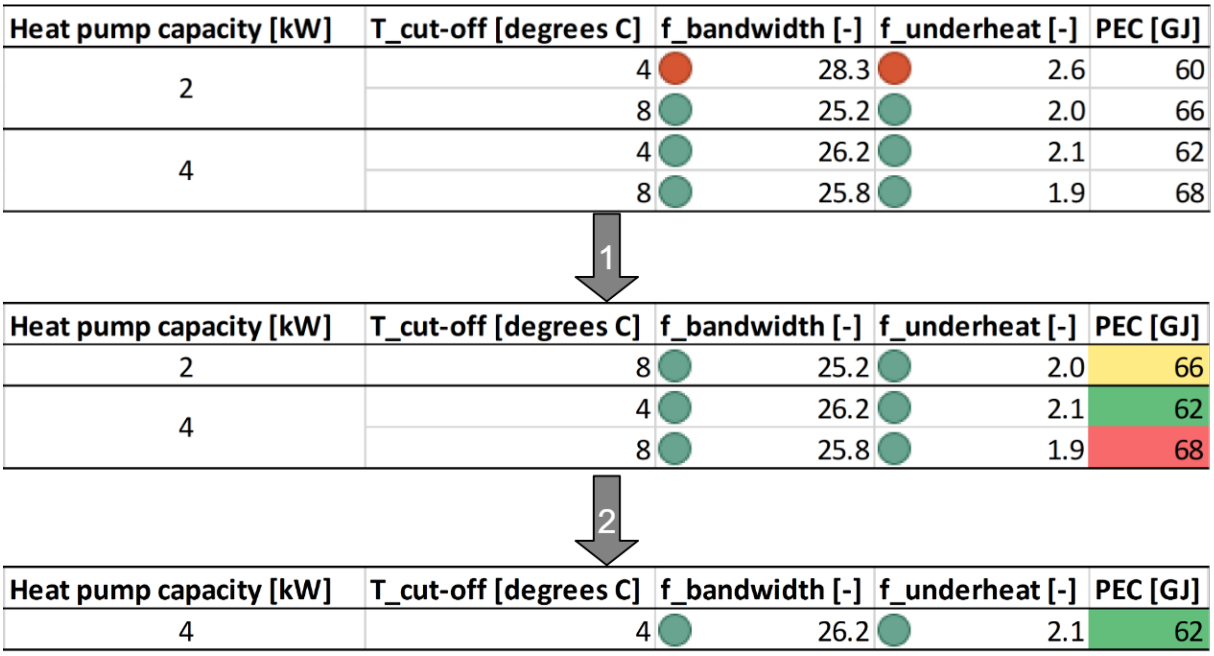
The left graph displays the bivalent alternative operation mode. In this mode, the heat pump in the HHP system is switched off below the bivalent temperature, as it is no longer able to supply enough heat to the building. Therefore the cut-off temperature of the heat pump is equal to the bivalent temperature ($T_{biv} = T_{cut\text{-}off}$). It is called the bivalent alternative operation mode because either the gas boiler is supplying space heating (blue area) or the air-water heat pump is supplying space heating (green area).

The right graph displays the bivalent parallel operation mode. In this mode, the heat pump is switched off when it is no longer able to supply heat more efficiently than the gas boiler. With a gas boiler efficiency of 96 %, a primary energy factor for gas of 1.15 and a primary energy factor for electricity of 2.5 (see Section 3.4 for details), the heat pump should no longer be operated when it has a COP lower than 2.1[2]. This is when the control system optimizes for the lowest primary energy consumption. However, other minimal COPs can result from optimizing on for example energy costs. In between the bivalent and cut-off temperatures both the heat pump and the gas boiler are producing heat (red area), but the heat pump is not able to supply enough heat to match the building load, even though it is still producing heat more efficiently than the gas boiler.

energy.

The final step in this method is to compare the chosen heat pump capacity and switching temperatures for the alternative bivalent mode with that of the parallel bivalent mode. For each insulation case, the hybrid heat pump system (i.e., capacity and operation mode) is chosen which has the lowest primary energy consumption.

In the hybrid heat pump system, DHW is produced by the gas boiler in the same way as with the mono gas boiler case described above. The temperature control system used by the gas boiler and the heat pump are equal to their respective individual cases (i.e., a PID controller for the gas boiler and an oscillating controller within a bandwidth for the heat pump).



Heat pump capacity [kW]	T_cut-off [degrees C]	f_bandwidth [-]	f_underheat [-]	PEC [GJ]
2	4	🔴 28.3	🔴 2.6	60
	8	🟢 25.2	🟢 2.0	66
4	4	🟢 26.2	🟢 2.1	62
	8	🟢 25.8	🟢 1.9	68

Heat pump capacity [kW]	T_cut-off [degrees C]	f_bandwidth [-]	f_underheat [-]	PEC [GJ]
2	8	🟢 25.2	🟢 2.0	66
4	4	🟢 26.2	🟢 2.1	62
	8	🟢 25.8	🟢 1.9	68

Heat pump capacity [kW]	T_cut-off [degrees C]	f_bandwidth [-]	f_underheat [-]	PEC [GJ]
4	4	🟢 26.2	🟢 2.1	62

Figure 3.4: Example case of method used to choose heat pump capacity for the alternative bivalent scheme. In this case the f-factors for the corresponding mono gas boiler case are $f_{bandwidth} = 26.3$ and $f_{underheat} = 2.2$.

3.3.3 Validation of building model

In order to provide some validation that the building model is producing a realistic heat demand, the output of the model is compared with the energy data of the example building by Agentschap NL (2011). The simulation model that uses the building with current insulation level and which is heated by a gas boiler has the same characteristics as the example building, thereby making it possible to compare the energetic results of the model with the data by Agentschap NL (2011). A building load curve displaying the heating load of the building over the outside temperature is also made by setting the inside temperature at 20 °C and oscillating the outside temperature between −20 °C and 20 °C. Data on the space heating demand was recorded by repeating this process 24 times. The produced building load curve is compared to the load curve resulting from the building load formula of Kemna (2014), when using the building characteristics of the studied building.

3.4 Present-day techno-economic assessments

The techno-economic assessments focus on energetic, environmental and economic factors to assess the studied systems. First, a present-day assessment is made to indicate what the techno-economic impact is of switching to any of the studied systems today (i.e., in 2018). To provide insight into what the techno-economic impact will be when switching to any of the studied systems in the future, a model is made in Microsoft Excel to calculate the energetic, environmental and economic impact of the scenarios made in Chapter 4.

The energetic factors that will be assessed are the primary energy consumption, the seasonal performance factor of the heat pump, the load factor of the heat pump, the gas and electricity use and the total energy use. The environmental factor considered is amount of CO_2 emissions related to the space heating and DHW production of the studied building. The primary energy consumption is calculated by using a primary energy factor for each of the considered fuels. The seasonal performance factor SPF is calculated by dividing the total amount of heat supplied by the heat pump Q_{HP} by the total electricity consumption of the heat pump E_{HP}, over a full year.

$$SPF = \frac{Q_{HP}}{E_{HP}}$$

In the hybrid heat pump systems, the load factor x_{HP} is calculated by dividing the amount of heat delivered by the heat pump for space heating $Q_{HP\text{-}sh}$ by the total amount of heat delivered to the space heating system Q_{sh}.

$$x_{HP} = \frac{Q_{HP\text{-}sh}}{Q_{sh}}$$

TRNSYS provides the output for the energy consumption in kilojoules. This is converted to natural gas use with the higher heating value (HHV) of natural gas, which is 35.17 MJ/m^3.

The primary energy factor used in the present-day assessment for electricity PEF_{elec} is 2.5. This value was derived from RVO.nl (n.d.) and checked with the reported efficiencies of electricity production in the Netherlands between 2000 and 2016 (CBS, 2018b). The used primary energy factor for natural gas $PEF_{nat.gas}$ is 1.15 (Esser & Sensfuss, 2016).

The environmental factor considered is the amount of CO_2 emissions related to the space heating and DHW production of the studied building. These will be calculated by using CO_2-intensity factors for the combustion of natural gas and the Dutch electricity mix. Renewable gas is assumed to have no net CO_2 emissions. The used value for the CO_2-intensity of electricity in the Netherlands is 0.49 kg/kWh, which was the CO_2-intensity in 2016[4] (CBS, 2018b). The used CO_2-intensity of natural gas in the Netherlands is 0.0565 kg/MJ, which was the CO_2-intensity in 2013 (Zijlema, 2012). The used gas price is 0.67 €/m^3 (Milieu Centraal, n.d.-d). The used electricity price for the present-day calculation is 0.22 €/kWh (van der Wilt, 2018).

The considered economic factors are investment costs C_{invest}, energy costs C_{energy} and net present cost (NPC, or total discounted costs)[5]. The NPC is calculated by discounting the costs of each year to its present value PV_t with a discount rate i over time t.

$$PV_t = \frac{C_{invest} + C_{fuel}}{(1+i)^t}$$

In this study, a discount rate of 3.8 % is used, which is taken from Lazzarin (2012), who studied the application of condensing boilers in building refurbishments. By summing these present values over the amount of years studied N, the NPC can be calculated.

$$NPC(i,N) = \sum_{t=0}^{N} \frac{C_{invest} + C_{fuel}}{(1+i)^t}$$

Tables depicting the used values for the investment costs related to the heat sources and insulation measures can be found in Appendix C.1. The amount of ISDE subsidy is also displayed there (more information on this subsidy can be found in Section 4.2.3).

3.5 Future techno-economic assessment of scenarios

To assess the future techno-economic impact of different scenarios for the studied heating systems, assumptions have to be made regarding the studied factors describe above. In the yearly “Nationale Energieverkenning” reports made by Energieonderzoek Centrum Nederland (ECN), predictions are made regarding the wholesale price of natural gas and electricity, the primary energy factor of electricity and the CO_2-intensity of electricity. For this study, the Nationale Energieverkenning 2017 (NEV 2017) report was used (ECN, 2017). However, price developments are also expected for investments in the heat sources and insulation measures, which will be described first.

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[4] CBS (2018b) calculates the CO_2-intensity of electricity in the Netherlands with a method focusing on the average CO_2 emissions related to electricity production, called the ‘integral method’, and with a method focusing on the marginal change in CO_2 emissions, called the ‘reference park method’ (Gerdes, Segers, Bosselaar, Verdonk, & Harmelink, 2012). The value used in this study is calculated with the integral method.

[5] Maintenance costs are not taken into account in this study, as the only data found on this reports a difference of 30 € per year between the different heat sources under study (Kemkens, 2018).

3.5.1 Investment cost developments

An overview of the developments in investment costs is given below. A table that provides the complete overview of the cost reduction values used in this study can be found in Appendix C.1. As the ISDE subsidy will end in 2021 (Regeling nationale EZ-subsidies, 2017; RVO.nl, 2018), it is not taken into account when calculating the investment costs of the heat sources in 2025 and 2040.

Heat sources In the report by Naber, Schepers, Schuurbiers, and Rooijers (2016), prognosis for the decrease of costs are made by making use of three different learning curves (i.e., no learning, slow learning and fast learning). For heat pumps they expect that the costs are 25 % lower in 2025 and 40 % lower in 2040 (i.e., fast learning). For gas boilers they expect a decrease of 10 % in 2025 and 20 % in 2040 (i.e., slow learning). When checking these values with the prognosis of van Melle, Menkveld, Oude Lohuis, de Smidt, and Terlouw (2015), it can be seen that both prognoses are similar, although van Melle et al. (2015) assume a cost decrease that is five percentage points larger than that of Naber et al. (2016).

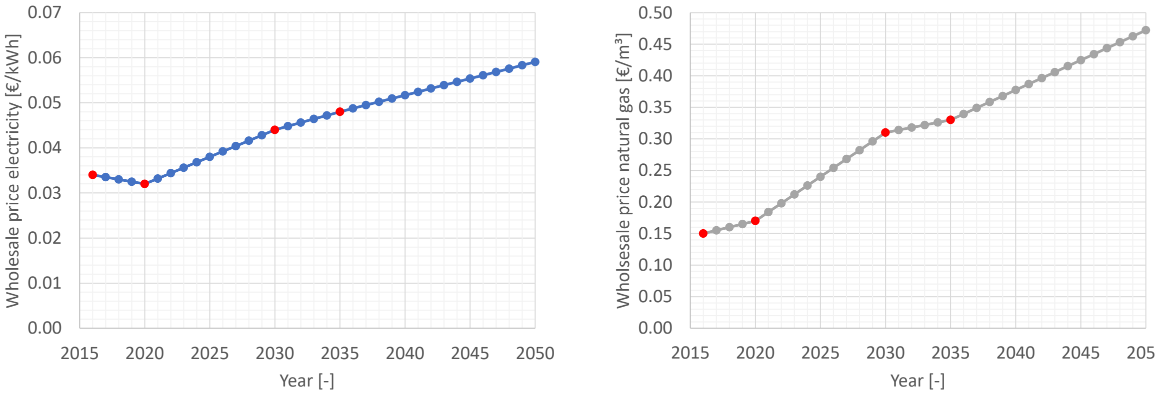
Insulation Naber et al. (2016) expects fast learning for net-zero energy building insulation measures and slow learning for other insulation measures. van Melle et al. (2015) expect a cost reduction of 15 % in 2025 and 25 % in 2040 for insulation measures in general. In this study, the high insulation level has a cost reduction of 15 % in 2025 and 25 % in 2040 while the improved insulation level has a cost reduction of 10 % in 2025 and 20 % in 2040.

Low temperature radiators Naber et al. (2016) expect slow learning for heat emissions systems, which corresponds to a cost reduction of 10 % in 2025 and 20 % in 2040.

3.5.2 Energy price developments

Wholesale price electricity and natural gas

For the wholesale prices of electricity and natural gas, predictions were made in the NEV 2017 report for 2020, 2030 and 2035. These values were linearly interpolated to produce yearly prices from now to 2035. However, because the scenarios continue until 2050, the price development between 2016 and 2035 was linearly extrapolated up to 2050. The wholesale price developments are depicted in Figure 3.5. It is important to note that these predictions are characterized by a high uncertainty due to its many complex interdependencies to other factors. For example, the prediction for the wholesale natural gas price in 2035 comes with a bandwidth of around +13 to −45 % (ECN, 2017).



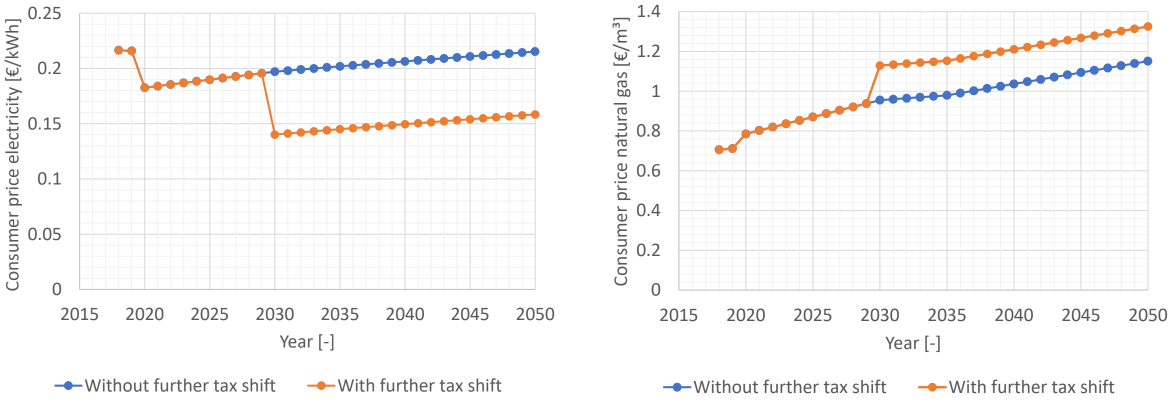
(a) Wholesale price development of electricity (b) Wholesale price development of natural gas

Figure 3.5: Inter- and extrapolated wholesale price development, based on data by ECN (2017), data points indicated in red

Consumer price electricity and natural gas

The wholesale price of electricity and natural gas only makes up a part of the price paid by consumers. First of all, energy companies do not directly charge the wholesale price to clients, but add value to the product and therefore the retail price is higher than the wholesale price. To estimate the future retail prices, the margin between past retail and wholesale prices is calculated. The past wholesale prices are taken from ECN (2017) and ECN (2016), while the past average retail prices are taken from CBS (2018c). The average margin of the years 2010, 2015, 2016 and 2017 is calculated. This margin is then applied to the wholesale price predictions of ECN (2017), which formed an estimate for the future retail price of electricity and natural gas.

Other components of the electricity price are the "Opslag Duurzame Energie (ODE)[6]", the energy tax and the value added tax (VAT). The ODE is 0.01 €/kWh and 0.03 €/m^3 and is assumed to be constant over time. The VAT is 21 % and is also assumed to be constant over time. However, the energy tax is adjusted according to the plans presented in the "Voorstel voor hoofdlijnen van het klimaatakkoord"[7] (Klimaatberaad, 2018). This constitutes a tax shift in 2020, from electricity to natural gas. The energy tax on electricity is to be decreased by 0.027 €/kWh, while the energy tax on natural gas is to be increased by 0.055 €/m^3. It is stated in Klimaatberaad (2018) that an energy tax decrease of 0.074 €/kWh for electricity and an increase of 0.2 €/m^3 for natural gas will result in large increase in attractiveness for insulation and sustainable heating alternatives. It will also be modelled how this further tax increase can influence the scenarios studied in this thesis. However, it is not stated when this further tax shift should occur. Therefore, it has been assumed that the second tax shift will occur ten years after the first tax shift; in 2030. Figure 3.6 shows the assumed future electricity and natural gas prices, including all components and the proposed energy tax shifts of 2020 and 2030.



(a) Consumer price development of electricity

(b) Consumer price development of natural gas

Figure 3.6: The assumed future electricity and natural gas consumer prices, including all components (i.e., retail price, ODE, energy tax and VAT) and the proposed energy tax shift of 2020 and the further tax shift in 2030

Fixed costs electricity and gas

Consumers also have to pay fixed costs for both the gas and electricity connection. Currently, the studied house is assumed to have a 1 x 35 A connection. In case of a switch to an all-electric heating system, this connection will probably need to be reinforced to a 3 x 25 A connection (Liander, n.d.). Currently, this entails no increase in the periodic fixed costs for electricity, just a one-off fee for reinforcing the connection (Liander, 2018a). Because this study focuses on the heating system, and the electricity connection is necessary irrespective of the heating system (e.g., for lighting and appliances), these fixed costs for electricity will only be taken into account if the grid connection is reinforced due to a change in

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[6] In English: increment sustainable energy.

[7] In English: proposal for the outline of the climate agreement.

the heating system (e.g., a switch to an all-electric heating system)[8]. For the gas connection, the switch to an all-electric system is assumed to be combined with a switch from using gas for cooking to using electricity for cooking. Therefore, the one-off disconnection costs for removing the gas connection as well as the removal of the periodic fixed costs for the gas connection, are both taken into account. These costs are retrieved from Liander (2018b). A table that specifies the fixed costs of both electricity and gas can be found in Appendix C.4.

Renewable gas price

In two of the considered scenarios, natural gas will be replaced by a renewable gas. This switch to a renewable gas will occur on the second natural switching moment, in 2040. As will be explained in Section 4.2.3, before renewable gas can be used on a large scale and for the heating of dwellings, it still has to be developed further. This makes assumptions on the pricing and scarcity of this fuel highly uncertain. However, some studies have already looked into the scarcity of green gas, which will be used in this thesis as well. Because there is even less data available on the economics of using renewable hydrogen in the built environment, green gas is chosen as the renewable gas under study here.

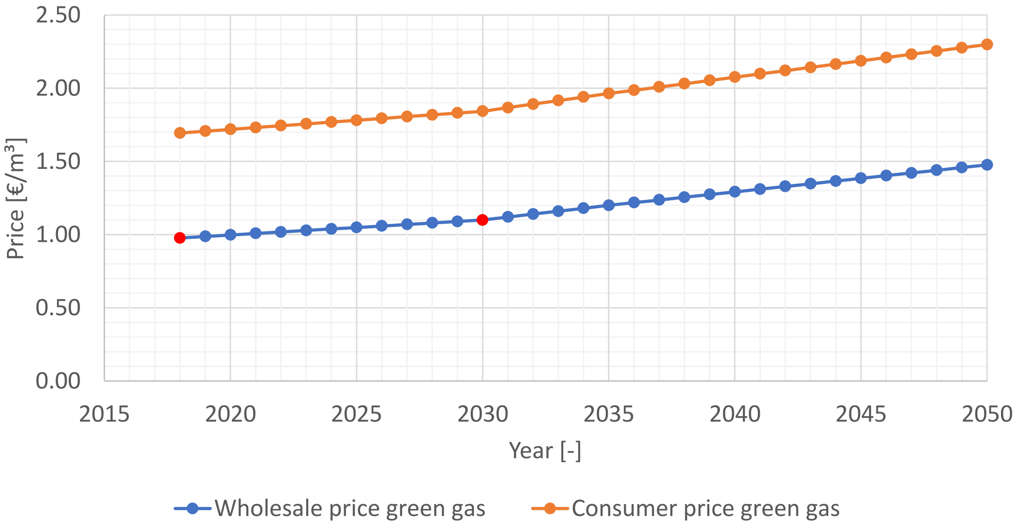

Figure 3.7: Assumed development of wholesale and consumer prices of green gas. Based on Van Mellle et al. (2018) and Schepers et al. (2015), indicated by the red marks

Van Mellle et al. (2018) state that the current production costs of green gas (i.e., biomethane) are 100 €/MWh$_{th}$, which corresponds to around 0.98 €/m^3. For the future cost development of green gas, first an assumption had to be made regarding the development in supply of green gas.

Lensink (2013) expects that the domestic production of green gas in 2030 is between 1.5 and 3.5 bcm and Groen Gas Forum (2014) expects a domestic production of 2.2 bcm. The available supply of green gas for the Dutch built environment is obviously not only dependent on domestic production as other factors significantly influence this supply such as the potential to import green gas, which can increase the available supply, but also the competition with other sectors, which have a priority over the built environment and therefore decrease the available supply (see Section 4.2.3 for more information).

In this study, it is assumed that the available supply of green gas for the built environment is 2 bcm in 2030. Schepers et al. (2015) state that with a cost price of 1.10 €/m^3, supply and demand will meet at 2 bcm of green gas. By interpolating between the current price by Van Mellle et al. (2018) and the future price by Schepers et al. (2015), a wholesale price development between 2018 and 2030 can be made. From 2030 to 2050, the wholesale price of green gas is coupled to price of electricity, as no data is available on the price development of green gas in that period. It was not coupled with the price of natural gas, as

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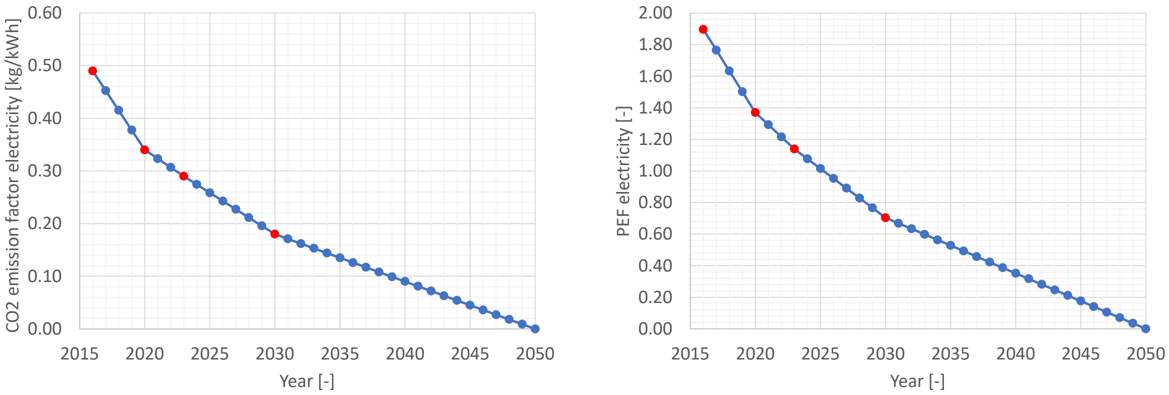
[8] The fixed retail costs for electricity will also not be taken into account, as these will always be present due to the use of electricity for lighting and appliances

electricity is becoming more and more renewable at that point, while natural gas is not. The wholesale price development of green gas is depicted by the blue line in Figure 3.7.

The difference between the consumer price and wholesale price of green gas is calculated in the same way as that of natural gas, with one main difference. The green gas price will not be influenced by the proposed tax shifts by the Klimaatberaad (2018). The consumer price development of green gas is depicted by the orange line in Figure 3.7.

3.5.3 Primary Energy Factor and CO_2-intensity assumptions

ECN (2017) also published predictions for the development of the primary energy factor and CO_2-intensity of electricity. The primary energy factor is a measure of the efficiency of the conversion of fossil energy resources to a final energy carrier or supply (i.e., electricity or heat). Therefore, the PEF of renewable energy is 0, as no energy resources are used up in the conversion of energy (i.e., the source is renewable). The process of producing yearly values for the PEF and CO_2-intensity was similar to the process explained for the wholesale prices of electricity and natural gas. The predictions for 2020, 2023 and 2030 were first interpolated with the values for 2016, after which the values in 2030 were extrapolated to a PEF and a CO_2-intensity of 0 in 2050 (i.e., a fully renewable electricity supply), which can be seen in Figure 3.8. For natural gas, the PEF and CO_2-intensity are assumed to be constant[9].



(a) CO_2-intensity development of electricity

(b) PEF development of electricity

Figure 3.8: Inter- and extrapolated CO_2-intensity and PEF development of electricity, based on ECN (2017), indicated by the red marks

3.5.4 Development in mix of green gas and natural gas

With regards to developments in the mix of gas the gas supply used in the studied building, projections of Gasunie (2018) were used. By comparing the projected supply of natural gas in the gas grid in 2030 and 2050 with the projected supply of green gas in the gas grid, it was possible to calculate what the ratio between green gas and natural gas could be in these years. According to Gasunie (2018), this gas mix will consist of 11 % of green gas in 2030 and 89 % in 2050. However, just as with the renewability of the electricity supply, it is assumed that the gas mix will have fully transitioned to a renewable supply of green gas in 2050 (i.e., 100 % green gas in 2050). Yearly values were interpolated between the current ratio and the projected ratios for 2030 and 2050 by producing a second degree polynomial trend line in Microsoft Excel, which can be seen in Figure 3.9a. For the consumer price of this gas mix, the ratio was applied on the consumer price of natural gas (without further tax shift in 2030, see Figure 3.6b) and of green gas (see Figure 3.7)[10], thus resulting in the price development visible in Figure 3.9b. The CO_2

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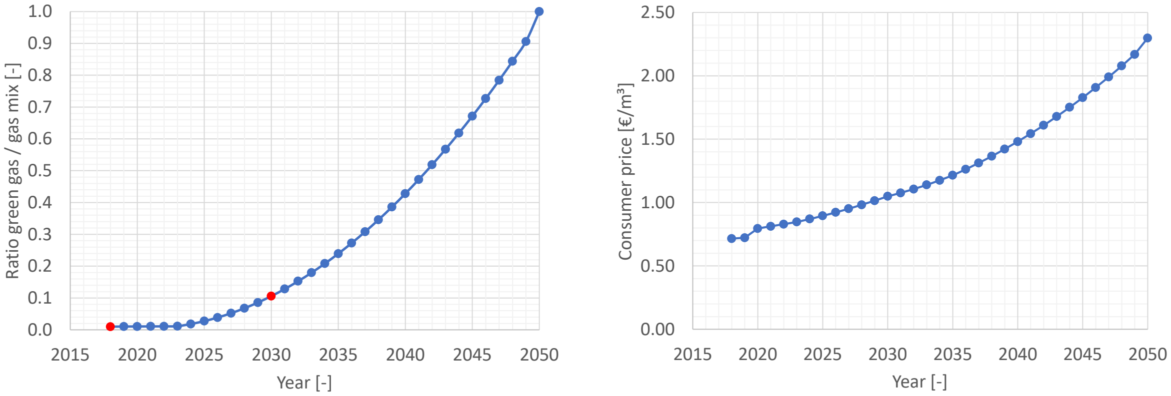
[9] The CO_2-intensity of natural gas has been roughly equal since 1990 up to 2013 (i.e., a decrease was reported of 0.0003 kg/MJ (Zijlema, 2012)).

[10] In reality, this way of pricing the supplied gas mix will be difficult, as the natural gas will be taxed differently than the green gas. But this administrative practicality is not taken into account in this study.

emissions and primary energy consumption related to gas use will also decrease as the share of green gas increases in the mix.



(a) Ratio of green gas in the Dutch gas mix, based on Gasunie (2018), indicated by the red marks

(b) Consumer price development of gas mix of green gas and natural gas

Figure 3.9: Assumed gas mix development and pricing between 2018 and 2050

3.5.5 Studied design options

The scenarios that will be made in Chapter 4 will provide different sequences for the heat sources used in the transition towards a low-carbon heat supply in 2050 for the studied building. However, there are multiple options with regards to what insulation measures to apply and when to apply them. As has been stated in Section 3.3.1, three insulation levels are studied with the extra possibility to diversify between low temperature and high temperature heat emissions systems. This results in many different options with regards to when to apply building adaptations from now until 2050, which will be called design options. Because of the many possible options, two rules are made to limit the amount of possible design options. First, as has been stated in Section 3.2.1, there are two natural switching moments when the heat source can be changed, in 2025 and 2040. Building adaptations can also only be applied at these moments. Second, only one large scale renovation will take place between 2018 and 2050, meaning that it is not possible to switch to the improved insulation level in 2025 and then switch to the high insulation level in 2040. However, it is possible to install a low temperature heat emissions system in 2040 after already applying insulation measures in 2025.

For each scenario made in Chapter 4, the design option with the high insulation measures applied at the earliest moment will be studied as well as the design option with no insulation measures applied at all, thus indicating the full range of design option studied from high to low. Next, extra design options are studied that are relevant for the scenarios. In total, 26 design options were studied, which can be found in Appendix C.2.

3.5.6 Decision method for choosing best design option

The four scenarios are compared by looking at all studied design options for each scenarios but also by choosing one preferred design option per scenario, which is most preferred from the perspective of a home owner. The criteria for deciding on the preferred design option is based on the lowest cost. This is done by summing the energy costs of each year with a yearly write-off of the investment costs. The investments in the heat source of the building are written-off in 15 years, which is also the assumed lifetime of the technologies. The investments in the building adaptations are written-off in 25 years, which is shorter than the lifetime of the building adaptations. These write-off periods are equal to those in Hers, Rooijers, and Meyer (2018) and in the report by Huurcommissie (2017). The home-owner will decide on what design option to go for based on the lowest yearly total costs (i.e., energy costs and written-off investment costs) in 2025 and 2040.

The scenarios and design options will also be assessed from the perspective of a policy maker, in which case there are two indicators taken into account. The first is the amount of CO_2 emissions saved in comparison with the business as usual case (i.e., keeping the current insulation level and heating the building with a gas boiler on natural gas until 2050). The second indicator, called the carbon reduction cost, is the cost per kg of CO_2 emissions saved, to give insight in the economic efficiency of the different design options and scenarios. The costs used in this calculation are the yearly costs that were introduced above, summed over the whole studied period. The amount of CO_2 emissions saved is calculated by comparing the CO_2 emissions related to the studied design options to a business-as-usual or reference case where the building continues to use natural gas in a gas boiler with the current insulation level up to 2050. It should be noted that the only costs taken into account are the costs for the home-owner, no societal costs are taken into account. Especially the costs of adapting the energy infrastructure is a societal cost that can be relevant for the policy maker.

Chapter 4

Scenario study

As indicated in Chapter 3, the scenario study will be structured around seven methodological steps, which will be dealt with in chronological order.

4.1 Step 1: Specification of objectives

The domain of this scenario study is the studied building case of Section 3.1. The time period is from 2018 up to 2050, when the emissions related to the heating of the built environment have to be completely diminished, according to the current cabinet (Wiebes, 2018a). The scenarios are structured around phases of 15 years, as the lifetime of most heating systems is around 15 years. The first natural switching moment for the heating system will be in 2025, and the second in 2040, thus resulting in three phases: 2018-2025, 2025-2040 and 2040-2050. The two last periods will be combined in step 5 and 6 as the home-owner will change to its final heat source and insulation level already in 2040. In the ten years following this decision the home-owner will not change anything in its heating system or its house, but the energy used by the home-owner will develop towards a fully renewable energy source, as has been explained in Section 3.5.

The goal of the study is to assess different transition paths towards a low-carbon individual heating system for the studied building case. As already indicated in Chapter 1, there is a pressing need to decrease the use of natural gas in the Dutch heating system for buildings. At the same time, the hybrid heat pump is put forward as a promising solution by some parties, while other parties have doubts regarding the applicability of the system and the threat of causing a lock-in on the natural gas infrastructure. A primary objective of this research is to assess the potential of the hybrid heat pump system in the studied building, in an unbiased way, and to compare this potential to the potential of all-electric air-to-water heat pumps and renewable gas.

The main users of these scenarios will be people active in the energetic renovation/improvement of the Dutch building stock. The scenarios will provide an insight into the future consequences of choices made today, regarding the heat supply of the Dutch building stock.

4.2 Step 2: Analysis of recent and ongoing dynamics

The analysis of the recent and ongoing dynamics is structured around the three levels of the multilevel perspective, which were explained in Chapter 2.

4.2.1 Regime analysis

Actor network

The main stakeholders in the regime are depicted in Figure 4.1. This stakeholder maps indicates the key relationships in case of private home ownership and an individual heat source (i.e., not heated by a collective heat grid).

The household is embedded in the neighbourhood and pays an energy company to supply electricity and/or gas used in the heating system of the building. The actual delivery of this energy source is done by network operators: transmission system operators (TSOs) and distribution system operators (DSOs). These actors are tasked with supplying energy through an infrastructure from the energy companies to the users, at a national and regional level for TSOs and at a regional and local level for DSOs.

The national government has set the task to transition to a low-carbon heating system in 2050 (Wiebes, 2018a), but the actual transition is to occur at the local level and lead by the municipalities. The municipalities are to decide what infrastructure will be installed at the neighbourhood level, in order to phase out the use of natural gas before 2050. The DSO advices the municipality on considerations regarding the energy infrastructure. The national government provides incentives to home owners to contribute to this transition through policy instruments and also supports the installations sector to train more employees for installing sustainable heating technologies (e.g., through the Green Deal C-224 (2018)).

The home-owners decide on what changes are made in their house with regards to insulation measures and heating system measures, for which they task builders and installers respectively to advice and install these measures.

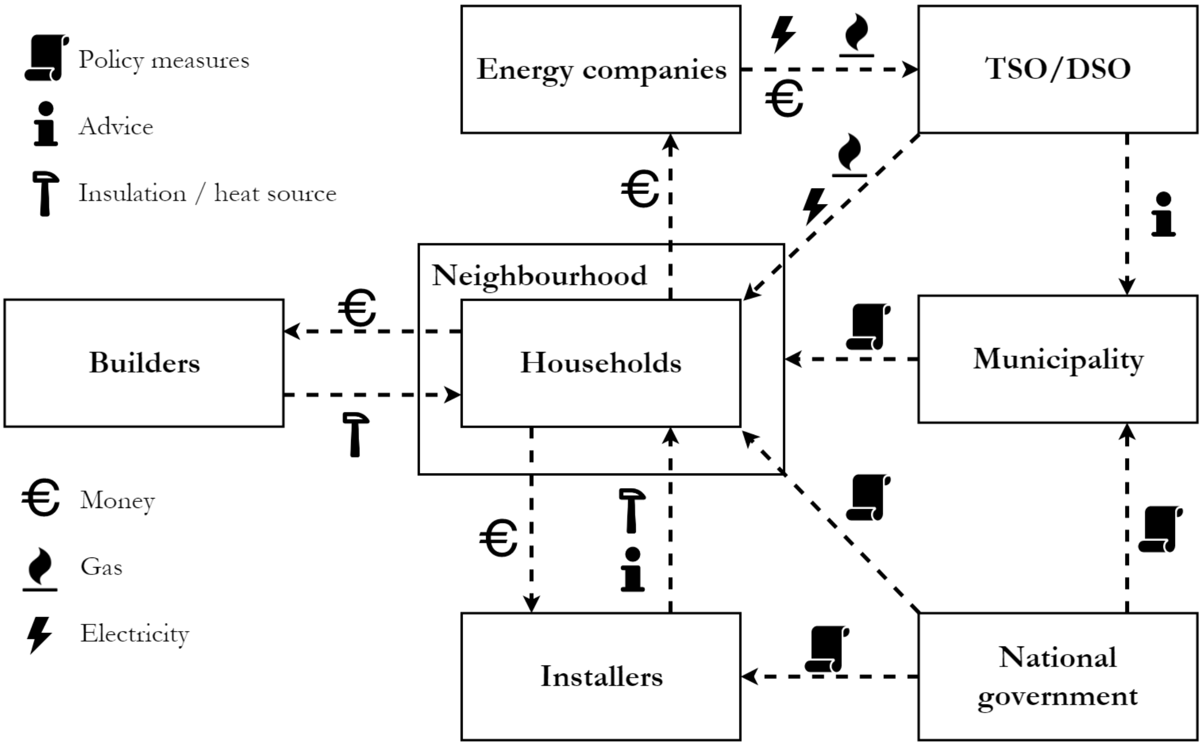


Figure 4.1: Stakeholder map with the main relations between the most important stakeholders in the heating system, in case of private home ownership and an individual heat source

Dominant heating technology

The dominant heating technology in the regime is the natural gas boiler. Almost every building (95%) in the Netherlands is connected to the gas grid, which account for around seven million natural gas boilers

(Schepers et al., 2015). Figure 4.2 displays the development of the consumption of natural gas by Dutch dwellings, which shows a decreasing trend. Dwellings account for around 70 % of the natural gas use by the Dutch built environment, with utility buildings accounting for the remaining 30 %. The consumption of this amount of natural gas results in a total CO_2 emission by Dutch houses of around nineteen million tonnes, which is around 10 % of total Dutch emissions (Schepers et al., 2015)[1].

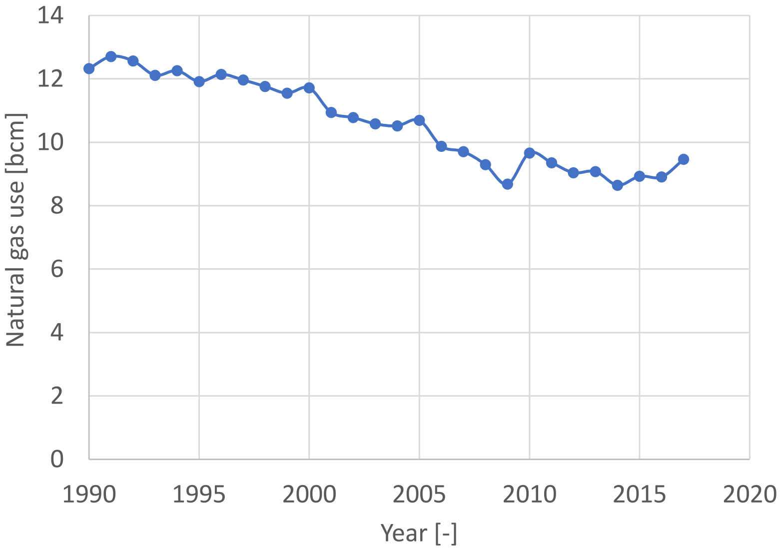


Figure 4.2: Development of yearly natural gas consumption by Dutch houses between 1990 and 2017 (CBS, 2018d)

Figure 4.3 shows how the HR (i.e., high efficiency) gas boiler has become the dominant heating technology for Dutch houses. In around 20 years the HR gas boiler has become the most installed heating device, replacing its less efficient predecessors. When using the lower heating value of natural gas, the HR107 boiler has a theoretical efficiency of 107 % due to the extra heat retrieved by the condensation of the flue gasses. The actual efficiency using the higher heating value was described in Section 3.3.2. Schepers et al. (2015) argue that one of the main reasons for the lowering natural gas consumption of Dutch houses is the high adoption rate of HR107 gas boilers.

The building that is used in the case study of this research uses high-temperature (HT) radiators to emit the heat from the central heating system to the room air. However, low-temperature (LT) heat emissions system can benefit the efficiency of the heating system. These can come in the form of radiators, convectors and wall- and floor heating systems.

Energy consumption in dwellings

When looking at Figure 4.2 and Figure 4.3 it can be seen that the natural gas consumption by dwellings is decreasing while the amount of dwellings is increasing. Apart from the increased efficiency of the heat source, RVO.nl (2017) states other causes for this development. The insulation rate of dwellings has increased. Most windows are double glazed and most roofs have been insulated. However, most floors and façades have not been insulated. Another cause is the changing climate, that has resulted in a decreasing amount of cold winter days in the Netherlands since twenty years (RVO.nl, 2017).

In terms of CO_2, existing buildings are responsible for 80 % of the emissions by the Dutch built environment. Nevertheless, 90 % of the reduction potential of the built environment lies with the existing buildings (Menkveld, Boerakker, & Mourik, 2005).

Another development can be seen when looking at the division between energy used for space heating and energy use for DHW. According to Schepers et al. (2015), space heating demand is decreasing while

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[1] According to Noailly and Batrakova (2010), the Dutch building sector account for 33 % of carbon emissions, which is significantly higher than the reported value by Schepers et al. (2015).

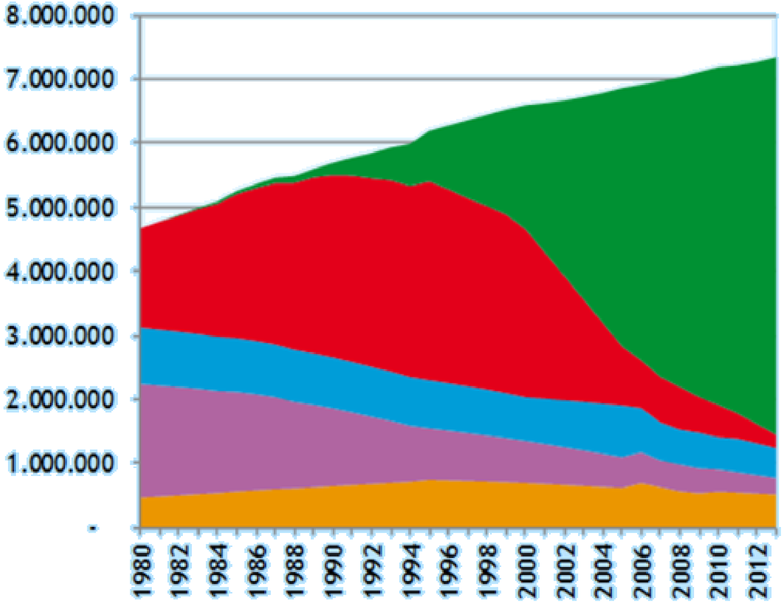


Figure 4.3: Heating device adoption by Dutch dwellings, with the amount of devices on the y-axis and the year on the x-axis. Green: HR gas boiler, red: VR gas boiler, blue: CR gas boiler, purple: gas heater, orange: block heating (Schepers et al., 2015)

DHW demand is increasing. Increasing insulation levels will result in the DHW demand becoming equal or larger than the space heating demand. However, RVO.nl (2017) also state that the 'combi boiler' has resulted in a decreasing natural gas use for DHW production.

Main policy developments

In general, Dutch policy aimed at the energy transition in the built environment can be described as consensus based and incentivising, as argued by Murphy, Meijer, and Visscher (2012). A large part of the national policies have been economic instruments (e.g., energy taxing, subsidies, loans). However, these economic instruments have received criticism because they are too fragmented and short-term oriented to create market stability and confidence (Murphy et al., 2012; Noailly & Batrakova, 2010; Tambach, Hasselaar, & Itard, 2010).

In the Energy Agenda by the Ministry of Economic Affairs (2016), low-interest loans are brought forward as measures to contribute to the carbon reduction target and to provide a sharper CO_2 reduction path for the built environment. However, Murphy et al. (2012) reports that low-income households, which is a specific target group for this policy, are uncommon in the applications received by financial institutions, thereby questioning its effectiveness.

In a study by Vringer, van Middelkoop, and Hoogervorst (2014) it was found that many home owners and tenants do not know many of the regulations regarding the energy efficiency of houses with tenants being less familiar with these policies than home owners. The Dutch national government has launched a three-year information campaign to inform citizens about energy efficiency policies (Ministry of Economic Affairs, 2016). However, such information campaigns are criticized by Murphy et al. (2012) as they are only effective at informing people that are sufficiently interested and motivated to help themselves with the information offered in such information packages, while van Middelkoop, Vringer, and Visser (2017) report that a large group of people are unaware and uninterested in the energy performance of their homes. People are also not easily convinced of the need to take energy performance improving measures for their houses, even if it offers a financial benefit (van Middelkoop et al., 2017).

Due to the safety risk resulting from the earthquakes in Groningen, the government has decided to significantly decrease the natural gas production in Groningen until 2030, when there should be no more natural gas extraction in Groningen. In addition to this, the set carbon targets have resulted in the goal to lower the natural gas consumption of the built environment (Wiebes, 2018a). The right to gas will be changed into a right to heat (Wiebes, 2018b) and the goal is to remove 30.000 to 50.000 houses per year from the gas grid in 2021 which will grow to 200.000 houses per year in the following years (Wiebes, 2018a).

If the 200.000 houses per year target is reached before 2030, 3.4 million tonnes of CO_2 will be saved according to the "Voorstel voor hoofdlijnen van het klimaatakkoord" (Klimaatberaad, 2018). The policies proposed in this document are aimed at enticing this transition to a low-carbon heating system for the built environment. It addresses the neighbourhood-approach where municipalities have a directing role to weigh what heating option is best for what neighbourhood, in which they are supported by national government bodies. Municipalities will have a 'transition vision' ready in 2021 which addresses the time line for the transition of its neighbourhoods (Klimaatberaad, 2018). The proposal to shift the energy tax from electricity to natural gas was already addressed in Section 3.5.2. However, the effectiveness of energy taxing on behavioural change is doubted in a report by Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (2011).

Another proposal is the building-bound financing scheme, where the repayment of the loan used for energy efficiency improvements of the house is transferred to the next owner in case of a switch of ownership. In this way, the loan is not bound to the person taking the loan but to the house in which the improvements are applied. A goal for this policy is to have the monthly expenses of the loan not be higher than the savings on the energy bill due to the improvements (Klimaatberaad, 2018).

The proposal also includes policy to improve the efficiency of heating devices, but it does not specify how this should be done. Builders, installers and energy suppliers have committed to a cost decrease of sustainable heating and insulation measures of 15 to 30 % in 2030, through standardization and scaling-up (Klimaatberaad, 2018).

In March 2018, sixteen parties signed a manifest that proposed that the government should enforce an efficiency requirement for domestic heating systems. This requirement is aimed at enticing progress in the transition towards low-carbon heating systems. A specific characteristic of this efficiency requirement is that it will ban the use of mono-gas boiler systems (Berenschot et al., 2018). "Vereniging Eigen Huis", a Dutch home-owners association, is against this requirement as the heating and insulation technology is not yet sufficiently developed and because this requirement will results in high costs for home-owners (de Ronde, 2018). Minister Wiebes is looking into different methods to phase out mono-gas boiler systems, but he is no proponent of a generic ban (de Ronde, 2018; Wiebes, 2017).

4.2.2 Landscape analysis

Groningen earthquakes

After the discovery of the natural gas fields under the province of Groningen in 1959, gas-induced earthquakes started to occur since the nineties. These earthquakes have grown in number and magnitude since then with the largest one occurring in August 2012 with a magnitude of 3.6 on the Richter scale (van Thienen-Visser & Breunese, 2015). Mainly the small villages surrounding the city of Groningen are affected with damages to houses, perceived unsafety, a faltering regional housing market and a reduced enjoyment of the environment (Woerdman & Dulleman, 2018). A conflict of interest has arisen between the inhabitants of Groningen, the gas producing companies and the national government because the gas production provides economic benefits for the whole country while the safety risk is only affecting the inhabitants (van der Voort & Vanclay, 2015).

As has been stated in Chapter 1, a safety report published in February 2018 led to the national government deciding to decrease the Groningen gas production immediately and to stop producing natural gas in Groningen altogether in 2030 (Wiebes, 2018a).

Sustainability discourse and targets

Chapter 1 also addressed the sustainability targets set in the 2015 Paris Agreement, where it was decided by almost every country in the world to drastically reduce the emissions of greenhouse gasses. The goal of the Dutch climate policy is to reduce the carbon emissions in 2030 to 49 % of the level in 1990. When considering the Dutch targets set in the context of the European Union, this percentage is 55 % (Klimaatberaad, 2018).

According to Costa-Campi, Jamasb, and Trujillo-Baute (2018), climate change and environmental concerns are transforming the operation and organisation of energy sectors, and renewed optimism about the possibility of achieving the sustainability targets has been found due to the decreasing costs of renewable energy sources and energy storage technologies.

Macro-economic and geopolitical developments

The Dutch Energy Agenda mentions the risks of geopolitical uncertainties to the energy transition, although it does not specify these risks (Ministry of Economic Affairs, 2016). However, in a report by the Clingendael International Energy Programme (2017) a specific risk of importing natural gas is mentioned, which is the uncertainty regarding a secure gas supply from Russia through Ukraine. This risk will become more relevant as the gas production in Groningen decreases.

In terms of macro-economic developments, the Dutch economy has been growing again since 2013 (i.e., in terms of GDP (CBS, 2018a)), while Costa-Campi et al. (2018) argue that the consumption of electricity is closely linked to economic growth. More specifically for the energy transition in the Dutch built environment, it is estimated that this transition will lead to an increase in system costs of 5 to 15 billion € per year (Ministry of Economic Affairs, 2016).

Electrification of other sectors

Also in other sectors than domestic heating, expectations have arisen to shift away from the use of fossil fuels and towards (renewable) electricity. One example is the mobility sector, where the Dutch national government, as well as local governments and companies expect that the adoption of electric vehicles will increase, especially for personal vehicles (Bakker, Maat, & van Wee, 2014; Ministry of Economic Affairs, 2016). Furthermore, the Dutch energy-intensive industry is preparing to stop using the low-calorific Groningen gas. One of the possible alternatives is electrification, according to the Dutch association for large-scale energy consumers (VEMW, 2018a, 2018b).

Energy infrastructure developments

The expectation of the Dutch gas TSO Gasunie (2016), is that in the energy transition towards 2050, less gas will be used in the Netherlands. Furthermore, the natural gas will be replaced by renewable gas in the future (more on renewable gas in Section 4.2.3). However, Gasunie (2016) does see an important role for the Dutch gas infrastructure to balance the renewable energy production and to act as a reliable back-up for local energy systems. A report by Van Mellle et al. (2018) also shows that the ‘optimal’ energy transition uses the existing gas network by combining electricity with renewable gas.

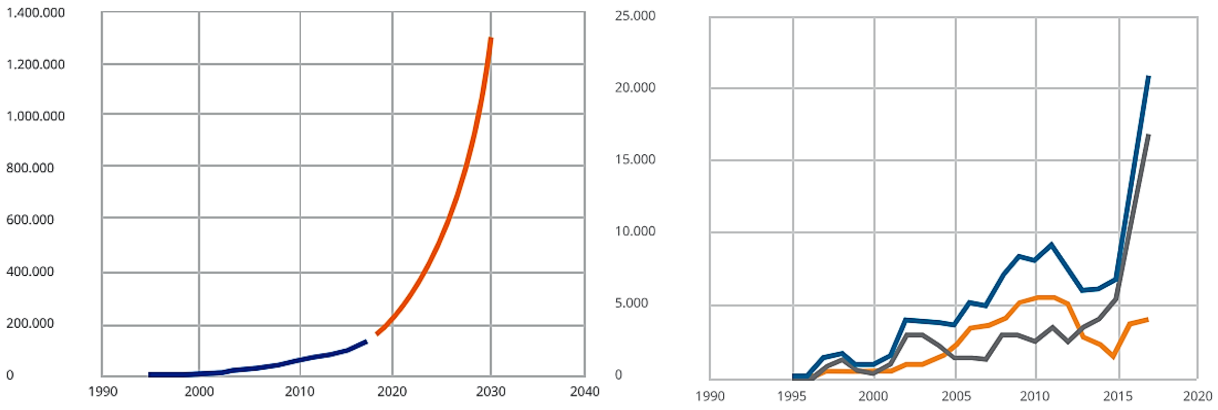
The energy infrastructure has a central role in the Dutch energy transition in the built environment as a guiding and facilitating factor. According to Schepers et al. (2015), the energy infrastructure decides what technical options are possible in an area but also offers possibilities to decide between different technological options. The energy infrastructure also comes with a lock-in effect, as they are built to last for a long time and require large investments (Schepers et al., 2015). Van Mellle et al. (2018) offer a different view by stating that we should not exclude any technology upfront from playing a long-term role, including the existing gas infrastructure which has already been paid for and is operating well.

Especially for the energy transition for Dutch existing houses, the replacement moment of the gas grid is a key moment to reconsider the source used for heating (i.e., choose to renew the gas grid or not). However, the current maintenance method used by DSOs can be considered as a reactive policy. The replacement of gas infrastructure is lead by risk assessments following leakages and malfunctions, and only for the specific parts that are not functioning. Because there is less of a proactive replacement policy, DSOs are less aware of where the gas grid is due to be replaced and on what term[2] (Schepers et al., 2015).

4.2.3 Niche analysis

All-electric air-water heat pumps

Figure 4.4a shows a prognosis made by the Dutch Heat Pump Association about the adoption of heat pumps in the Netherlands. The current growth will continue up to 2021 due to the assumption that heat pumps will become the dominant technology in newly built houses. After 2021 the adoption of heat pumps in existing housing is also assumed to strongly grow. In 2030, 200.000 heat pumps will be placed in existing housing per year, compared to a current market for gas boilers of 400.000 per year. After 2030 and up to 2050, a continuation of this growth can be expected because it is expected that at that point still six million houses have to switch to a low carbon heating system (Heynen, Groot, Vrisekoop, Witkop, & Kolenbrander, 2018).



(a) Prognosis of the amount of heat pumps in the Netherlands. The y-axis displays the total amount of heat pumps and the x-axis displays the year. The blue line is historical data and the orange line is the prognosis

(b) Yearly sales of heat pumps in the Netherlands. The y-axis displays the yearly sales of heat pumps. Grey line: air-source heat pumps, Orange line: ground-source heat pumps, Blue line: total amount of heat pumps

Figure 4.4: Graphs displaying a prognosis and historical data regarding the sales of heat pumps in the Netherlands. Figures from Heynen et al. (2018)

Figure 4.4b depicts the amount of yearly sales of heat pumps. The blue line displays the total amount of heat pumps sold per year, the grey line depicts the amount of air-source heat pumps sold and the orange line the amount of ground-source heat pumps sold. It can be seen that recently, the air-source heat pump has become the dominant technology over ground-source heat pumps, in terms of sales. The strong growth of heat pumps since 2016 can be explained by the introduction of the ISDE subsidy (explained on the next page), according to Heynen et al. (2018).

With the strong growth in sales, the heat pump has shifted away from the early adopters and entered the mass market. This mass market is more costs sensitive and more risk-aversive, according to Heynen et al. (2018). There are several barriers that have to be overcome for the mass introduction of heat pumps to succeed, which will be dealt with next. Note that the focus of this section is on air-water heat pumps, although some barriers are also applicable to ground-source heat pumps.

For an air-source heat pump, the efficiency is lowest when the ambient air is cold, therefore its peak demand coincides with low efficiencies, causing a high demand for electricity. This has two main implications. First, the system has to be designed so it can still accommodate the heat load in cold weather and second, the electricity grid should be able to cope with the high electricity demand. In the case that

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[2] There is an exception for gas grid made out of grey cast iron, as these are due to be replaced between 15 and 25 years (Schepers et al., 2015).

a large part of the neighbourhood switches to air-source heat pumps, the electricity grid should likely be reinforced, also due to the simultaneity of the electricity demand (Schepers et al., 2015; Van Mellle et al., 2018). The Dutch Heat Pump Association (DHPA) states that they are developing heat pump systems that can interact with the electricity grid as one of the solutions to this barrier (Berenschot et al., 2018). Furthermore, air-source heat pumps will likely require a larger electricity grid connection of the house, for which the consumer has to pay[3] (Damste et al., 2017).

The use of an air-source heat pump will also likely require building adaptations for existing housing. Heat pumps are most efficient with a low temperature heat emission system and in a building which is well-insulated (Damste et al., 2017). Schepers et al. (2015) state that there are no barriers to apply these adaptations to buildings before 2050.

Other barriers are a lack of knowledge by both consumers and installers, according to Damste et al. (2017). Berenschot et al. (2018) add that there is a shortage in the number of professional installers which are knowledgeable about heat pumps, especially in terms of low-temperature heating systems and when adjusting the system when putting it in commission. Another barrier is the nuisance resulting from the noise created by air-source heat pumps (de Ronde, 2018). The DHPA states that they are working on decreasing these environmental impacts including the noise created and space usage by heat pump systems (Berenschot et al., 2018).

Air-source heat pump systems currently require a significantly larger investment than gas boilers. This, combined with an inadequate stimulus for energy saving in existing buildings, results in the need for an attractive financing arrangement for consumers (e.g., rental propositions from energy or installations companies) (Berenschot et al., 2018; Damste et al., 2017). The Dutch national government provides a subsidy for investments in sustainable energy, called “Investeringssubsidie duurzame energie (ISDE)”, from which buyers of air-source heat pumps can make use. The height of the subsidy depends on the thermal capacity of the heat pump. The subsidy will stay in place up to 2021 (Regeling nationale EZ-subsidies, 2017; RVO.nl, 2018).

Hybrid heat pumps

The hybrid heat pump has been brought forward as a promising technology that offers benefits in a broad scale of applications (e.g., former minister of economic affairs Henk Kamp expected that a considerable share of the heat for existing housing will be produced by hybrid heat pumps (Kamp, 2015)), but which also has some barriers. One of the main benefits is that it can provide a significant reduction in gas use on a short time scale. According to Ouden et al. (2017), around 50 to 75 % reduction in gas use is possible with hybrid heat pumps. The air-source heat pump serves as the baseload and covers up to 40 % of the yearly peak. Due to the usage of the existing gas and electricity infrastructure and the independence on deep renovations, the introduction of hybrid heat pumps can occur much faster than other competitors of the gas fired boiler (Van Mellle et al., 2018). The prognosis displayed in Figure 4.4a also includes the heat pumps that are part of a hybrid system.

Because the heat pump does not have to supply the complete peak demand of the building, there is no need for a reinforcement of the electricity grid and less need for peak-load back-up from conventional electricity plants (Gasunie, 2016; Van Mellle et al., 2018). According to Berenschot, BDH, and DNV GL (2016), the simultaneous peak electricity load of multiple houses with a hybrid heat pump is only 20 % higher than that of houses with a gas fired boiler (i.e., 1.2 kW instead of 1.0 kW). A hybrid heat pump has the potential to switch between gas and electricity, thus providing flexibility to tackle congestion on the electricity grid (Damste et al., 2017; Gasunie, 2016). According to Gasunie (2016), hybrid heat pumps prevents lock-in because it postpones the need for reinforcement of electricity grids now and will prevent it altogether in the future when local seasonal heat storage has become more developed. Ouden et al. (2017) argue that hybrid heat pumps do not result in a lock-in situation as the lifetime of the installation is short (i.e., 15 years) and no infrastructure adaptations are required, thus leaving the option open to shift to another heat source after that relatively short period of time.

Another benefit the hybrid heat pump provides is that extreme insulation measures and low temperature heat emission are not required. This lowers the costs and makes the adoption rate of this technology quicker than for example an all-electric option (Gasunie, 2016; Van Mellle et al., 2018). Because lower

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[3] As has been stated in Section 3.5.2, this currently only entails a one-off fee and no extra periodic costs.

insulation levels are required, heat entrapment in summer is limited thereby providing a possibility to avoid increasing demand for cooling (Van Mellle et al., 2018). These benefits are most relevant for existing housing. Although a hybrid heat pump operates more efficiently with low temperature heating, it is also applicable with high temperature heating (Damste et al., 2017; Ouden et al., 2017).

In terms of costs, the most significant savings of the HHP, compared to an all-electric heat pump system, are due to lower renovation costs (Van Mellle et al., 2018). Ouden et al. (2017) argue that the investment costs of hybrid heat pumps still provides a barrier, even with the ISDE subsidy, although that does support the adoption rate. However, Damste et al. (2017) report that with a lower electricity price or higher gas price, there will be savings in total costs compared to the mono-gas boiler system.

Other barriers are similar to that of the all-electric air-source heat pump. For example, the produced noise, the knowledge level of consumers and installers[4], and the lack of a mandatory incentive for existing buildings to change its heat source (Damste et al., 2017; Ouden et al., 2017). Another barrier is that the installation method of hybrid heat pumps is not standardized yet, even though the devices themselves are mature and reliable, according to Ouden et al. (2017).

The association for the Dutch heating industry, VFK, states that they are improving hybrid heating systems on the following factors: the efficiency, use of space, noise level, refrigerants with a low global warming potential, cost efficiency, applicability with renewable gasses, flexibility services, and simple installation and maintenance. They are also investing in the training of installers to become more acquainted with these new heat sources (Berenschot et al., 2018).

Renewable gas

Renewable gas is a general term for a gaseous energy carrier produced from a renewable energy source (e.g., biomass or renewable electricity). With regards to the costs of these gasses, Speirs et al. (2018) state that the available options will be more expensive than the existing gas system. However, Van Mellle et al. (2018) point out that the costs of maintaining the gas infrastructure are more than offset by the investment costs avoided in the electricity grid (i.e., due to the required grid reinforcement resulting from electrification of for example heating systems). However, Van Mellle et al. (2018) also acknowledge that renewable gas will be scarcer than natural gas, and therefore it will not be feasible to cover the complete heat demand in the long term. The Dutch government is committing to the development of technologies that can scale up the production of renewable gas, and point out that the built environment is competing with other sectors for the use of renewable gas, in particular the transport and industrial sectors (Ministry of Economic Affairs, 2016). Another important main benefit of renewable gas in general is that it can provide flexibility and storage in the energy system utilising existing infrastructure (Damste et al., 2017; Speirs et al., 2018).The greenhouse gas intensity of different renewable gas options varies significantly according to Speirs et al. (2018). In this analysis, only hydrogen and green gas will be considered in more detail.

Hydrogen can be classified into three types according to the source of energy used to produce it. Grey hydrogen is hydrogen produced from fossil fuels (e.g., natural gas), blue hydrogen is produced in the same way as grey hydrogen, but the CO_2 that is emitted during the process is captured and stored underground (i.e., using carbon capture and storage; CCS). Green hydrogen is hydrogen produced by electrolysis, using renewable electricity. The use of hydrogen for heating the Dutch built environment has been voiced as an option, but also comes with high levels of uncertainty. According to Gigler and Weeda (2018), using hydrogen for use in the heating of buildings needs to be further developed (i.e., it is at a low technology readiness level). There is also uncertainty with regards to how hydrogen should be delivered to Dutch houses, what safety measures are needed and what the costs will be (Gigler & Weeda, 2018). According to Sadler et al. (2016), hydrogen appliances for domestic use needs to be further developed. There are a few models on the market, but sales are low. Damste et al. (2017) adds that with regards to safety, it is still unclear what the exact risks are when applying it in houses (e.g., with regards to older, less maintained piping), and that safety perception is also an important factor. The main high-pressure gas transport and distribution network is however largely suited to transport hydrogen (Hermkens et al., 2018; van den Noort, Vos, & Sloterdijk, 2017). The use of hydrogen in the built environment will have to

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[4] Because the customers of installers do not ask for (hybrid) heat pump systems (or are unmotivated due to the high costs), the installers do not see the necessity to educate themselves in these systems, resulting in installers not advising to install these systems, according to Ouden et al. (2017).

compete with other sectors that receive priority (e.g., high temperature industry, biochemical industry, ammonia production, seasonal energy storage) (Gigler & Weeda, 2018; Natuur en Milieu, 2018). Lastly, the mixing of hydrogen with natural gas in the gas infrastructure was considered by Gigler and Weeda (2018). They found that this is not preferred as the filtering of hydrogen from natural gas is a costly process which can deteriorate the quality of the gas.

When biogas, produced from biomass, is improved to natural gas quality, it is called green gas (Damste et al., 2017). As green gas has the same quality as natural gas, it can be directly mixed into the natural gas in the current gas infrastructure[5]. Furthermore, using green gas to heat houses does not entail any adaptations in the building or on the behaviour of its occupants (Schepers et al., 2015). Green gas is significantly more expensive than natural gas (Section 3.5.2 provides more information on the production costs of green gas). The largest barrier in the large-scale use of green gas for heating the Dutch built environment is the scarce supply. The Netherlands has a limited potential supply of biomass. Lensink (2013) states a potential of 0.15 to 0.6 bcm of green gas in 2020 and 1.5 to 3.5 bcm in 2030. Groen Gas Forum (2014) states a potential of 0.75 bcm in 2020 and 2.2 bcm in 2030. When comparing this to the 10 bcm of natural gas used by Dutch houses in 2017 (see Figure 4.2), it can be concluded that there is a short supply of biomass in the Netherlands for the production of green gas. Also in the case of green gas, the built environment is competing with other sectors on the availability of the energy carrier. Damste et al. (2017) state that other sectors have priority over the built environment, as there are less renewable alternatives for these sectors. Schepers et al. (2015) state that the utility sector will require 8 bcm of green gas, the industry sector 5 bcm and that 3 bcm will be required as a resource. This last number increases even more if more applications of sustainable biomass are developed for a biobased economy (Damste et al., 2017). A final competitor for using green gas in the built environment is using green gas for the production of electricity and heat in combined heat and power (CHP) plants (Damste et al., 2017). It is possible to import green gas to significantly increase the supply, but there is a large uncertainty regarding the pricing as there is no global market for green gas yet. Furthermore, it can be assumed that other countries will also want to use green gas, making the amount of possible imports uncertain as well (Damste et al., 2017; Schepers et al., 2015). It has been calculated by Van Mellle et al. (2018) that there is a production potential of 98 bcm of green gas in Europa anually by 2050.

Extra insulation measures

As has been stated earlier, Schepers et al. (2015) see no barriers to insulate the Dutch buildings accordingly before 2050, but it is desirable if only one renovation is required to make the houses ready for the transition to a low carbon heating supply. Menkveld et al. (2005) do state that a long time line for the insulating of houses is required, as it is dependent on renovation, refurbishment or rehousing, which does not occur often. Installing more extensive insulation measures does have a large impact on residents (Van Mellle et al., 2018), even though home owners stated in a study by van Middelkoop et al. (2017) that this ‘hassle’ does not discourage them from applying insulation measures.

4.3 Step 3: Inventory of potential linkages

For the inventory of potential linkages, three clusters of potential linkages have been formed.

Cluster 1: hybrid heat pumps, hybridization and stepping stone

The first cluster of linkages can be found in the hybridization between the air-source heat pump (niche) and the gas fired boiler (regime), which together forms the hybrid heat pump. The hybrid heat pump decreases the use of natural gas, which links up with the landscape pressure coming from the Groningen earthquakes and the sustainability targets, as well as with the policy measures that are a reaction to these pressures. The hybrid heat pump will require no infrastructure changes. It does require building adaptations, but the barrier of high investment costs might be overcome by building bound financing. The proposed tax shift from electricity to gas will also benefit the hybrid heat pump, but not as much

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[5] It should be noted that biogas cannot be fed into the gas infrastructure, and will require a separate infrastructure if the facility converting the biogas to green gas is not on the same site where the biogas is produced (Damste et al., 2017).

as an all-electric system. The hybrid heat pump can act as a stepping stone technology towards both an all-electric system and a system that uses green gas in combination with hybrid heat pumps. When the HHP acts as a stepping stone towards an all-electric system, it has mainly performed its stepping stone function by providing some relief on the pressure to reinforce the electricity grid and to adapt the building to be heated with a low temperature system. When the HHP acts as a stepping stone towards a system using green gas, it has mainly performed its stepping stone function by lowering the gas use of buildings and to buy time for building adaptations to occur, so that the scarce green gas can be used efficiently.

Cluster 2: path dependency on the use of gas

In the second cluster, the lock-in on natural gas continues (regime) due to path dependency. Hybrid heat pumps and/or green gas options (niche) can make use of this path dependency by exploiting the existing gas infrastructure (landscape) while still reducing the use of natural gas. This also saves costs and hassle due to the less extensive building adaptations that are expected to be required. These cost savings can provide some relief on the landscape development that the energy transition will have a large economic impact.

Cluster 3: no longer any gas consumption

The third cluster of linkages is found when the landscape pressure coming from the Groningen earthquakes and the sustainability targets, and the resulting natural gas consumption reduction policy by the government, links up with the all-electric system offered with air-source heat pumps. It is already clear that using natural gas to heat the built environment in the future will no longer be possible. If that links up with the uncertainty regarding the scarce supply of green gas, it might provide a window of opportunity for all-electric systems. Extra insulation measures and a low temperature heating system will save energy in any case, which might lower the barrier to invest in these building adaptations. The barrier of high investment costs for this niche could also be overcome with the building bound financing scheme, combined with the tax shift from electricity to natural gas.

4.4 Step 4: Design choices

In a technological view, the hybrid heat pump can have three different roles in the transition towards a low-carbon heating system. One is to have no significant role, another is to be a stepping-stone towards an all-electric heat pump system, and lastly as an end-solution by complementing the system with renewable gas. However, it is also possible to skip the hybrid heat pump as a stepping-stone and go straight towards implementing an all-electric system. This simple overview of options leads to four different scenarios, which are displayed in Table 4.1.

Table 4.1: Technological overview of scenarios

Name	**Intermediate technology**	**Final technology**
HHP as stepping stone (S1)	Hybrid heat pump	All-electric heat pump
HHP as end-solution (S2)	Hybrid heat pump	Hybrid heat pump and renewable gas
All-electric start (S3)	All-electric heat pump	All-electric heat pump
Postponing change (S4)	Natural gas boiler	Renewable gas boiler or all-electric heat pump

The role of the main landscape pressure in the four scenarios is that pressure is applied to decrease the natural gas use and emit less CO_2 resulting from heating Dutch dwellings. The goal of all scenarios is a heating system that runs on renewable energy in 2050. Figure 4.5 displays the scenarios, the used heat sources and the natural switching moments in 2025 and 2040. Some heat pump manufacturers produce heat pumps that can be used as an add-on to existing gas boilers. However, this option is not considered in this study as the changing of the heat sources is synchronised on the two natural switching moments.

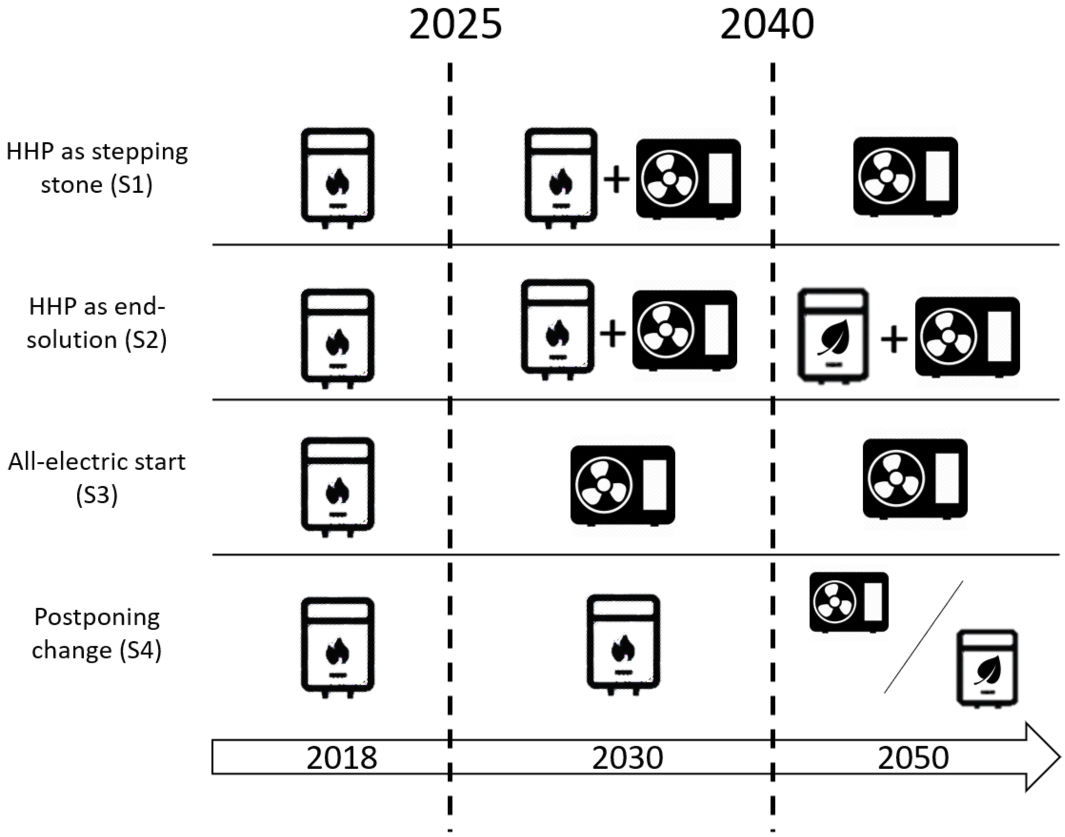

Figure 4.5: Schematic of the chosen scenario designs; the displayed heat sources are a natural gas boiler, a hybrid heat pump, an air-source heat pump and a renewable gas boiler (indicated by the leaf)

4.5 Step 5: Develop scenario architectures

The architecture of the scenarios is based on the following five main characteristics: the trajectory type (i.e., from Geels et al. (2016)), the main driving forces, the actor networks, rules & institutions, and technology. The scenario characteristics can be structured per scenario and per period; 2018-2025 and 2025-2050. The developments in the first period will lead to a decision on the heating system in 2025. In the second period, developments occur that lead to a decision on the heating system at the next natural switching moment in 2040. Then, a heating system has to be chosen that will run completely on renewable energy in 2050.

As both HHP scenarios, S1 and S2, are equal in the first period from 2018 to 2025 (i.e., both switch to a HHP system in 2025, after which the two scenarios branch off), they share the same scenario characteristics in the first period.

A complete overview of the scenario architectures of the four difference scenarios, split up over different periods, can be found in Table 4.2. The next step will elaborate the scenarios.

Table 4.2: Overview of scenario architectures

Scenario	**Trajectory typology**	**Main driving forces**	**Technology**	**Actor networks**	**Rules & institutions**
HHP as stepping stone (S1) & HHP as end-solution (S2) Period: 2018-2025	·Transformation trajectory	·Progress towards renewable heating system ·Use less natural gas ·Uncertainty regarding final heat source, no lock-in preferred	·Hybridization of natural gas boiler and ASHP: HHP ·HHP as stepping stone ·HHP as quick-fix	·Incumbents are key, partially reorientate, diversification ·Installers train for broader knowledge base ·Strong relationship installers - gas boiler industry ·Municipalities in control, mainly for collective solutions ·Home owners reactive	·Conversion mechanism ·Regulative rules: economic instruments, ban stand-alone gas boiler ·Normative rules: sustainability and affordability of domestic heating ·Cognitive rules: habits of using natural gas for heating/cooking
HHP as stepping stone (S1) Period: 2025-2050	·Transformation trajectory ·Similarities with technological substitution trajectory	·Electrification of households ·Scarcity of renewable gas	·HHP was stepping stone to ASHP ·Full reorientation to ASHP	·Full reorientation of incumbents ·Municipality decides for all-electric, or home owners proactive in switch ·Installers more acquainted with heat pumps, better relationship with heat pump manufacturers	·Conversion mechanism ·Regulative rules: economic instruments, ban use of natural gas ·Normative rules: sustainability of domestic heating, energy independence and security ·Cognitive rules: habits of natural gas for heating/cooking let go
HHP as end-solution (S2) Period: 2025-2050	·Transformation trajectory	·Renewable gas affordable ·Quick-fix preferred	·Partial reorientation towards other form of hybridization: HHP with green gas ·Full reorientation not possible due to scarcity of green gas ·HHP on natural gas was stepping stone	·Second partial reorientation of incumbents, to green gas ·Installers well acquainted with hybrid heat pumps, good relationship with manufacturers ·Governed by municipality, or partly by home owners	·Conversion mechanism ·Regulative rules: economic instruments, ban use of natural gas (gradually) ·Normative rules: sustainability of domestic heating, comfort ·Cognitive rules: habits of using gas for heating/cooking
All-electric start (S3) Period: 2018-2050	·Technological substitution trajectory ·Similarities with transformation trajectory	·Gaining momentum movement to stop using natural gas ·Proactive home owners	·Substitution of natural gas boilers by ASHP in 2025 ·Full reorientation ·Infrastructure investments and sunk costs	·Transition carried bottom-up by new entrants and proactive home owners ·Power struggles, socio-political mobilizaiton	·Displacement mechanism ·Regulative rules: economic instruments, ban stand-alone gas boiler ·Normative rules: bad image of natural gas, Groningen, sustainability, energy security ·Cognitive rules: full electrification, also mobility
Postponing change (S4) Period: 2018-2025	·Transformation trajectory	·Uncertainty alternative heating technologies ·Trust in natural gas boiler ·Unwillingness large investments and hassle	·Natural gas boiler replaced by newer model ·No infrastructure changes	·Incumbents use defensive hedging ·No clarity from municipality	·Layering mechanism ·Regulative rules: only subsidies ·Normative rules: affordability of domestic heating ·Cognitive rules: habits of using natural gas for heating/cooking
Postponing change (S4) Period: 2025-2050	·Transformation trajectory or technological substitution trajectory	·Urgeny of change ·Scarcity of renewable gas	·Scarcity green gas: switch to green gas or all-electric ASHP	·Incumbents or new entrants carry transition ·Municipality in control, home owners reactive ·High workload installers	·Displacement mechanism ·Regulative rules: economic instruments, ban natural gas in domestic heating ·Normative rules: sustainability of domestic heat

4.6 Step 6: Elaborate all scenarios

Here the four scenarios will be elaborated, structured in the same way as presented in Table 4.2, so per scenario and per period.

4.6.1 2018-2025: HHP as stepping stone (S1) & HHP as end-solution (S2)

One of the main driving forces in the first period of these two scenarios is the necessity to progress towards a renewable heating system, as a response to the increasing landscape pressure from the changing climate and the resulting sustainability targets. Using less natural gas is also a separate driving force as a response to the safety issues resulting from the earthquakes in Groningen. As there is still unclarity about what heat source will fit best in each neighbourhood, a solution that leaves multiple options open and does not result in lock-in, is preferred. This entails that large infrastructure changes and investments should be avoided. A so-called 'quick fix' solution is preferred.

When looking at the actor network, the incumbents are in the centre of the transition, as they partially reorientate away from just using natural gas for space heating and DHW production, as a reaction to the socio-political debate regarding the energy transition and Groningen gas production. Industry actors move towards diversification by still exploiting the existing technological capabilities in the gas boiler technology but by also introducing renewable heating technologies. A partial reorientation takes places where sustainability factors receive more attention by incumbents. For example, installers train to have a broader knowledge base regarding different heating technologies and gas boiler manufacturers diversify to hybrid or all-electric heat pumps. Similar to the actor network in the old regime, installers have a strong relationship with the gas boiler industry, especially in terms of support services.

Municipalities are in control for guiding the transition of the neighbourhoods towards a renewable heating system. However, this directing role is more prominent in collective solutions such as heat grids, and less for individual heating systems. In 2021 the municipality has to provide the plans about which neighbourhoods will be disconnected from the natural gas grid before 2030. In this scenario, the municipality decides that the neighbourhood from the case study will not be switching to a heat grid or all-electric solution before 2040, so the natural gas grid will remain present for that period. The home owners are not proactive in switching to a different heat source than natural gas, due to high investment costs and uncertainty about the future heating system.

Policy develops by not only having the goal to transform to a low-carbon heating system in 2050, but also to consume less natural gas as soon as possible. This fits the 'conversion mechanism' of institutional change as described by Thelen (2003) in Geels et al. (2016), where the goals of policy instruments are changed, while not changing the instruments themselves (see Chapter 2). In terms of regulative rules, mainly economic instruments will be used (e.g., subsidies, building-bound financing and tax shifts). A ban for stand-alone natural gas boiler systems is also possible in this scenario. In terms of normative rules, the transition to a sustainable system remains an important goal to strive for. However, heating should remain affordable for home owners. A cognitive rule that is present is that consumers are accustomed to heating and cooking on natural gas and trust these products. However, the information supply for alternative technologies is increased.

Due to the above-mentioned interactions, a shift is made to a hybrid heat pump system in 2025. As the name suggests, this can be seen as a hybridization between the natural gas boiler and the air-source heat pump. This technology will decrease the natural gas use while acting as a stepping stone towards a range of renewable heating technologies. By using the current infrastructure and because it depends less on the building envelope being highly insulated, the hybrid heat pump provides a quick-fix for houses in neighbourhoods that will not be disconnected from the natural gas grid. The air-source heat pump can be seen as a complementary technology or add-on which decreases the natural gas used for space heating, while keeping in place the trusted gas boiler technology.

The dynamics that have been explained above fit the updated transformation trajectory concept by Geels et al. (2016), where the regime is gradually reorientating through adjustments of incumbents. These incumbents partially reorientate towards providing sustainable alternatives as an add-on to the existing regime technology, which can be seen as technology diversification. This reorientation process interacts with changing rules and institutions that result in a demand for a more sustainable heating system that uses less natural gas, but which remains affordable.

4.6.2 2025-2050: HHP as stepping stone towards all-electric(S1)

In this period of the first scenario, two main driving forcing can be identified. The further shift to the full electrification of households and the scarcity of renewable gas. These two driving forces also interact with each other. As the share of renewable sources in the electricity supply increase, the environmental sustainability of using electricity in dwellings also improves. Due to the scarcity of renewable gas, and the prioritization of other sectors over domestic heating, the next step for households if full electrification instead of the "greening" of the gas supply (i.e., increased environmental sustainability of gas by using renewable gas). The complete electrification of dwellings also fits with the electrification of other sectors, such as mobility (e.g., with the adoption of electric vehicles).

In the actor network, incumbents take the next step to fully reorient towards all-electric systems, after partially reorientating towards the hybrid system. For example, energy companies only supply electricity to households and DSOs only operate the electricity grid. In this scenario-step, it is possible that the municipality decides that the neighbourhood is switching to an all-electric system (i.e., by removing the gas grid, reinforcing the electricity grid and not installing a heat grid) or that the home owners are more proactive and switch over to an all-electric system before the municipality decides on what system to use. In the latter case, the electricity grid might have to be reinforced as a response to the increased use of all-electric systems, instead of reinforcing the grid in anticipation of a switch to these systems. Because of the previous shift to hybrid heat pump systems, installers have become more acquainted with the use of heat pumps in domestic heating systems, and also have tighter relationships with heat pump manufacturers, making them more confident to advice positively on all-electric systems in existing housing.

When looking at the development of rules and institutions, a conversion mechanism of Thelen (2003) can be identified, as the goal of policy shifts from using less natural gas to using no natural gas in domestic heating systems. In terms of regulative rules, a continuation of the economic instruments for discouraging using natural gas and encouraging energy saving or sustainable energy production measures can be present or, if the municipality decides to remove the gas grid, a ban on the use of natural gas can also become a regulative instrument. In terms of normative rules, the goal of a fully sustainable heating system remains. In addition to this, energy independence and energy security also become more important, both on the scale of the households, where a combination of solar PV and an all-electric heating system make the households more energy independent, as on a larger national scale, where the renewable and natural gas supply are both dependent on imports, leading to energy security concerns. In terms of cognitive rules, with the stepping stone role of the hybrid heat pump, the traditional relationship between (natural) gas and domestic heating has been loosened, increasing trust in other sources.

The above mentioned dynamics result in a further shift in the heating technology, with the hybrid heat pump acting as a stepping stone towards the full electrification of the heating system of households with an all-electric air-source heat pump. The stepping stone function of the hybrid heat pump has been fulfilled by allowing more time for the infrastructure to prepare for such a shift (i.e., removing the gas grid, reinforcing the electricity grid) and by allowing more time for the complementary technology of higher insulation levels and low-temperature heat emitters to be applied to existing housing. By acting as a stepping stone, the hybrid heat pump has made a full reorientation to the all-electric air-source heat pump system in 2040 possible.

When placing this scenario in the transition trajectory typology of Geels et al. (2016), the scenario described above falls somewhere in between the transformation trajectory and the technological substitution trajectory. In the transformation trajectory, the transition is carried by incumbents, which is also the case here, however the shift to an all-electric system cannot be considered to be a completely gradual reorientation. The decision to stop using gas in households is a radical change. Therefore, this scenario also has similarities with the technological substitution trajectory, where the hybrid heat pump is substituted by the all-electric air-source heat pump. By using the hybrid heat pump as a stepping stone to an all-electric system, this scenario has similarities with the 'fit-and-conform' concept of Smith and Raven (2012). The HHP has a larger fit with the regime's institutions than the ASHP but does pave the way towards the all-electric system. However, elements of the 'stretch-and-transform' concept can also be identified, as this paving of the way by the HHP also involves changing the regime's institutions.

4.6.3 2025-2050: HHP as end-solution (S2)

One of the key differences to the main driving forces present in the 2025-2050 scenario-step of S1 is that renewable gas is not too scarce and is therefore affordable for use in domestic heating systems. In this scenario, preference is given to another 'quick-fix' for switching from the hybrid heat pump system on natural gas to a fully renewable system. Due to the required infrastructure, insulation and heat emitter changes, the all-electric option cannot be considered a 'quick-fix'.

In this scenario-step, the incumbents partially reorientate again, after doing so already when the switch was made to the HHP (Section 4.6.1). This time they partially reorientate towards renewable gas due to green gas becoming less scarce. However, the supply of green gas is not large enough to fully reorientate to just using green gas in domestic heating. Due to the previous shift to the hybrid heat pump system on natural gas, installers have gotten acquainted to installing both heat pumps and gas boilers, and have a good relationship with the manufacturers of these hybrid heat pump systems. In this scenario, the municipality can either specifically decide not to remove the gas grid and reinforce the electricity grid, or the shift can take place ungoverned by the municipality, where home owners decide themselves what heat source to use. However, home owners cannot influence what gas is delivered to the dwelling, as their gas supply is connected to the larger gas network.

Just as with the scenario-step described in Section 4.6.2, a conversion mechanism of rules and institutions can be identified. The goal of policy shifts from using less natural gas to using no natural gas in domestic heating systems. The regulative rules show a continuation of the economic instruments of discouraging using natural gas and encouraging energy saving or sustainable energy production. However, a complete ban of natural gas in domestic heating is also possible. If the condition of a fully renewable heating system has to be met, the gas has to be completely renewable and not mixed with natural gas. However, this ban can also be introduced gradually, by increasing the mixing ratio of green and natural gas. The prominent normative rules in this scenario-step are again the sustainability of domestic heating, and assured thermal comfort. A cognitive rule that is present is that households are accustomed to heating and cooking on a gas.

Due to the dynamics described above, a partial reorientation towards another form of hybridization occurs in 2040 where the hybrid heat pump is a combination of an air-source heat pump and a gas boiler that will run on 100 % renewable gas in 2050. Due to the limited availability of green gas, a full reorientation towards only using renewable gas in mono gas boiler systems is not possible. Here the hybrid heat pump on natural gas has acted as a stepping stone again, by lowering the gas demand and by buying time for the scaling up of green gas production. By switching towards a hybrid heat pump on green gas, the hybrid heat pump has become an end-solution where the switch to green gas can be seen as a diversification step or as an add-on to the hybrid heat pumps system.

The described dynamics fit the continuation of the transformation trajectory typology of Geels et al. (2016). The switch from natural to renewable gas can occur gradually (e.g., by increasing the mixing ratio of renewable and natural gas) or radically (e.g., by fully switching from natural to renewable gas), and is carried by incumbents. By providing renewable gas as an add-on to the hybrid heat pump technology, the last step to a fully renewable heating system is taken. This step can be seen as technology diversification by incumbents. This reorientation process is a result of changing rules and institutions that focus on sustainability, affordability and comfort.

4.6.4 2018-2050: All-electric start (S3)

In the all-electric start scenario, the main driving forces are the gaining momentum of the movement to get rid of (natural) gas in the built environment (e.g., #vangaslos), in response to the increasing landscape pressure from the sustainability movement and the consequences of the Groningen gas production, as well as the more proactive attitude of home owners.

In this scenario, the actor network changes more significantly, with the transition being carried by new entrants that offer extensive all-electric solutions for existing dwellings. It is also possible that incumbents fully reorient, but the transition has a more bottom-up characteristic where not the incumbents but new entrants and home owners themselves carry the transition. The home owners are more proactive and do not wait for the neighbourhood plans from the municipality, although it is possible that the municipality also decides to go for an all-electric system. Power struggles and socio-political mobilization of the movement to get rid of (natural) gas in the built environment gain momentum through increasing landscape pressure and influence home owners to move away from using natural gas for domestic heating and hot water production when the next natural switching moment for their heat source occurs in 2025.

Looking at the development of rules and institutions, a resemblance with the displacement mechanism by Thelen (2003) can be identified, where new institutions replace existing ones. Especially in terms of normative rules a large change occurs, where the use of natural gas has a bad image due to the consequences of the Groningen earthquakes, the sustainability movement and the energy security concerns regarding natural gas (i.e., if the Groningen gas production decreases significantly, the natural gas has to be imported). In terms of regulative rules, the government instruments do not differ significantly from the other scenarios, with mainly economic instruments to discourage the use of natural gas and encourage energy saving and sustainable energy production measures. A ban on the mono-gas boiler also fits this narrative.

Due to the dynamics described above, the current heating system with natural gas boilers is substituted by an all-electric system with an air-source heat pump in 2025. A full reorientation of technology takes place, which can be seen as a radical and disruptive change. A large scale shift in neighbourhoods requires significant infrastructure investments by DSOs and results in sunk costs in the present gas grid. In 2040, the air-source heat pump is replaced by a newer model.

This transition fits the technological substitution trajectory by Geels et al. (2016), with resemblances to the transformation trajectory. The technology substitution is accompanied with large institutional change. The transition has similarities to the transformation trajectory because it is not only carried by new entrants, but also by incumbents. However, the incumbents have a more reactive position (e.g., if the municipality does not decide on an all-electric system, but the DSO acts reactively when more people switch to all-electric heating systems). This scenario can involve power struggles due to the high investment costs required for building renovation and the sunk investments in the gas grid. Elements of the 'stretch-and-transform' concept by Smith and Raven (2012) can be identified in this scenario, as institutions are adapted to suit the niche-innovation (e.g., 'living without natural gas' or 'aardgasvrij wonen', and the movement to get rid of (natural) gas, '#vangaslos'). However, policy changes such as the shift from a right to gas to a right to heat or the ban on mono-gas boilers are not specifically aimed at the niche of all-electric air-water heat pumps but also to other niches that do not (solely) use natural gas.

4.6.5 2018-2025: Postponing change (S4)

The main driving forces in this scenario-step are the uncertainty regarding the alternative heating technologies, the trust in the gas boiler as a heating source and the unwillingness for large investments and hassles that accompany the alternative heating technologies.

The incumbents do not respond to the pressures arising from the sustainability movement and the Groningen earthquakes by reorientating towards other technologies, but use defensive hedging: existing capabilities are exploited while exploring for new alternatives. This results in a focus on green gas, which can directly use the existing gas infrastructure. In this phase, the municipality is not able to provide clarity to home owners with regards to new plans for alternative heating sources. Therefore home owners stick with the old regime technology.

The development of rules and institutions can be characterized with the layering mechanism of Thelen (2003): new policies are layered on top of existing policies but do not change their core logic. In this case, the policies still largely focus on energy-saving measures. However, regulative, normative and cognitive rules do not change significantly. No tax shift or building-bound financing is introduced to entice the shifting of fuels away from natural gas. Normative rules mainly develop around the affordability of domestic heating, the barriers of high investments and the hassle that comes with building renovations. A cognitive rule that remains is the habit of using natural gas for heating and cooking.

In terms of technology, the natural gas boiler is replaced by a newer model in 2025. Infrastructure changes are not necessary, but the share of green gas in the gas mix is slowly increased.

The dynamics described above fit the transformation trajectory by Geels et al. (2016) the most because of the slow shift to green gas. The regime remains relatively stable under the landscape pressures due to the uncertainty regarding the alternative technologies, stable actor network and the low institutional change.

4.6.6 2025-2050: Postponing change (S4)

In the next scenario-step of the "Postponing change" scenario, the main driving forces are the urgency that a change in heating system is necessary to reach the target of a sustainable heating system in 2050 and the scarcity of renewable gas.

Incumbents either partially reorientate to renewable gas or incumbents fully reorientate to an all-electric system with an air-source heat pump. It is also a possibility that new entrants take over this role from the incumbents, by supplying services to switch to all-electric systems. The municipality is in control regarding what infrastructure is placed in the neighbourhood, home owners act reactive to the decision of the municipality (e.g., to remove the gas grid or not). Due to the short time frame available to switch to a fully renewable system, the workload of installers and builders should also be taken into account, especially with regards to renovation measures.

The displacement mechanism of Thelen (2003) fits best when describing the institutional change, where new policies take over existing ones. The existing policy was focused on energy saving measures, while the new ones are aimed at bringing about a change in heating technology towards a renewable alternative. Regulative rules include economic instruments and possibly a ban on the use of natural gas in domestic heating. The main normative rule is the sustainability movement that has to adhere to the sustainable heating target in 2050.

As indicated earlier, a key factor in the choice of heating technology in 2040 is the scarcity of renewable gas. In the case that there is a large enough supply of renewable gas, only a partial reorientation towards renewable gas is necessary. However, when renewable gas is too scarce, a more disruptive switch towards an all-electric system is necessary.

When placing these developments in the typology by Geels et al. (2016), the transition can go in either of two trajectories. If renewable gas is widely available, a transformation trajectory occurs where incumbents partially reorientate towards green gas. If this is not widely available, a technological substitution trajectory occurs, where the gas boiler is substituted by an all-electric air-source heat pump.

4.7 Step 7: Reflection

In the first scenario (i.e., HHP as a stepping stone to all-electric), the stepping stone function of the hybrid heat pump can be clearly identified as the HHP is a hybridization between the current gas-based system and the envisioned future all-electric system. The main goal is to eventually get rid of using gas for the heating and DHW system, but in a more gradual, planned, and less disruptive way.

Elements of the stepping stone function can also be identified in the second scenario (i.e., HHP as end-solution), but not as clearly as with the first. As the hybrid heat pump significantly reduces the gas use, it makes it possible to use the limited supply of green gas in more dwellings. The HHP is not a stepping stone to a completely new system (i.e., from the current gas-based system to a partly gas-based system in the future), but it can be considered a stepping stone to the use of a new renewable fuel in the existing infrastructure. At the end of this scenario, the HHP is a hybridization between an electric and a green gas-based system.

The most radical shift can be found in the third scenario (i.e., all-electric start). The main driving force differs from the first two as the goal is to stop using (natural) gas for the heating and DHW system of the building. So, no gradual transition takes place to first decrease the gas use, but this stepping stone is skipped by applying an immediate shift to an all-electric system.

The fourth scenario (i.e., postponing change) is characterised by postponing the decision on what new heat source to use as a result of uncertainty regarding the new proposed alternatives. The old regime remains more stable for longer, but some change does occur by shifting the focus to green gas. When time is running short, it has to be decided to either go for an all-electric system, in which case this scenario will start having similarities with the third scenario, or to stick with the gas-based system but on green gas. In the latter case, the transition to a low-carbon heating system is completed without the introduction of a new heat source, but only by changing the fuel used by the old regime technology (i.e., the gas boiler).

Chapter 5

Simulation results

In this chapter, the focus is on presenting the results from the TRNSYS simulation models. First, some validation will be given regarding the building model. Then attention will be paid to the system sizing of the all-electric and hybrid heat pump models. Third, the techno-economic implications of the results will be presented for the present-day analysis (i.e., applying the studied heat sources in 2018). Finally, the different heat sources will be compared in terms of energetic, economic and environmental factors.

5.1 Validation of building model

To provide some validation of the building model and the associated heating load, the gas use of the current and improved insulation levels of the simulation model can be compared to the figures provided by Agentschap NL (2011) regarding the used example building. The gas use of the current level in the simulation model is 1883 m^3 while the gas use of the example building is 2030 m^3. For the improved insulation level, the gas use of the simulation model is 1132 m^3 while the gas use of the example building is 1050 m^3. Furthermore, the building load curve displayed in Figure 5.1 in blue was checked with the formula by Kemna (2014) for the building heat load of terraced houses, when the building characteristics of the current building are used, of which the output is plotted in orange[1]. It was found that a linear decrease from around 8 kW of space heating load at $-20\,°C$ to 0 kW at $20\,°C$ can be considered a realistic building load curve for the studied building.

It can be concluded that the model produces a heat demand that is relatively similar to the results of the example building. This does not provide validation to determine the exact energy use of a typical household, but does provide a realistic building to compare the impact of the different heat sources under study.

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[1] Agentschap NL (2011) does not provide a yearly figure on the building heat load of the example building, making it is only possible to compare the yearly gas use.

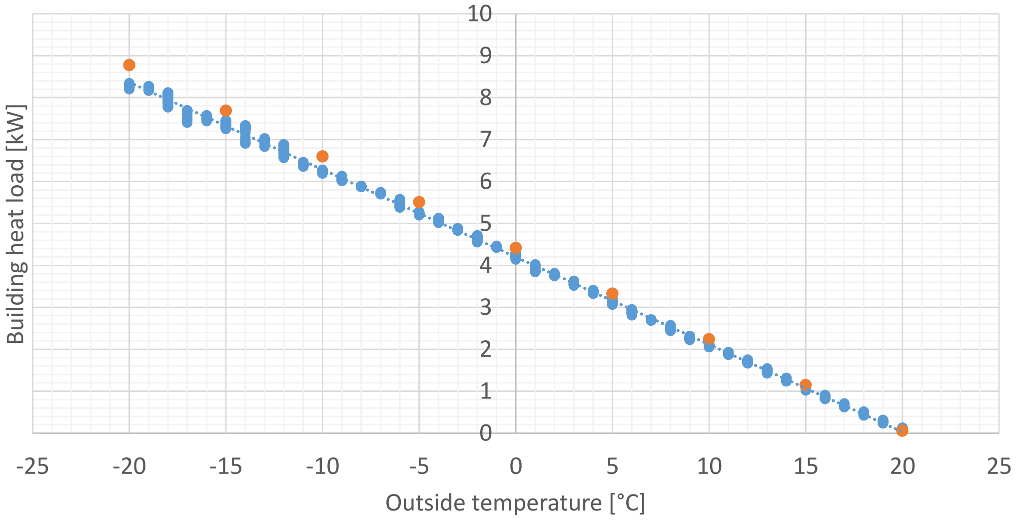


Figure 5.1: Building load for space heating plotted over the outside temperature of the studied building case. Data from the model is plotted in blue. Data from the formula of Kemna (2014) is plotted in orange.

5.2 System sizing of ASHP and HHP models

As has been explained in Section 3.3.2, the capacity of the gas boiler is equal in all studied cases, but for the hybrid heat pump and the all-electric air-source heat pump, a choice had to be made for the sizing and operation of the system that met certain criteria. The outcome of this search will be dealt with in this section.

5.2.1 System sizing of the air-source heat pump

The first criteria when choosing the capacity of the ASHP in the all-electric system was that the building should be heated at least as adequate as with the mono-gas boiler case with a similar insulation level. This was done with the f-factors that were defined in Section 3.3.2, for which the criteria was that $f_{ASHP} < (1 + \alpha) \cdot f_{gas}$ with $\alpha = 0.05$. Table 5.1 depicts both f-factors for the mono gas boiler cases. It can be seen that with higher insulation levels, the room temperature falls short of the temperature setpoint less often (i.e., $f_{underheat}$ is lower). However, when looking at both under- and overheating, indicated by $f_{bandwidth}$, it can also be seen that the building overheats more often with increasing insulation levels.

Table 5.1: f-factors for mono gas boiler cases

Insulation level	Current	Improved	High
$f_{underheat}$	2.1	1.9	1.6
$f_{bandwidth}$	25.6	27.8	43.7

The results displaying the f-factors for the different heat pump capacities studied in the all-electric ASHP case, for the different insulation levels, can be found in Appendix D.1.1. Figure 5.2 depicts the f-factors for the current insulation level in a graph. It can be seen that the $f_{bandwidth}$ shows a decreasing trend with increasing heat pump capacity. This is also the case with the other insulation levels. It can also be seen that the $f_{bandwidth}$ shows a decreasing trend for the current insulation level. However this is not the case for all insulation levels. The high insulation level shows an increasing trend of $f_{bandwidth}$ with increasing heat pump capacity.

The heat pump capacity was chosen where the adequate heating criteria was met, with the lowest heat pump capacity. A lower heat pump capacity also resulted in a lower primary energy consumption, as can

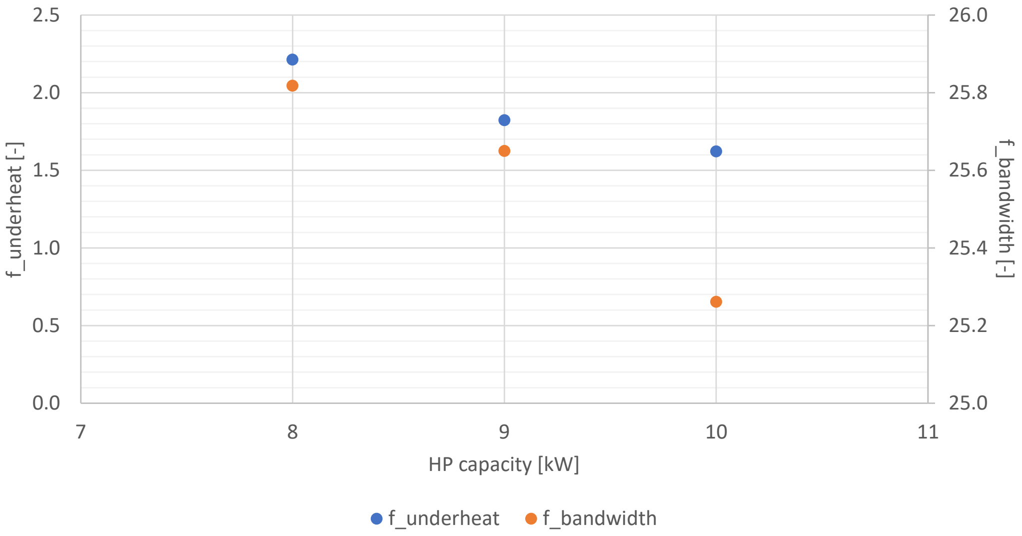


Figure 5.2: f-factors for current insulation level with an all-electric ASHP for different heat pump capacities

be seen in Appendix D.1.1. For the current insulation level this resulted in a thermal capacity of 9 kW, for the improved insulation level this resulted in a thermal capacity of 6 kW (both for the HT and LT radiators), and for the high insulation level this resulted in a capacity of 4 kW.

5.2.2 System sizing of hybrid heat pump

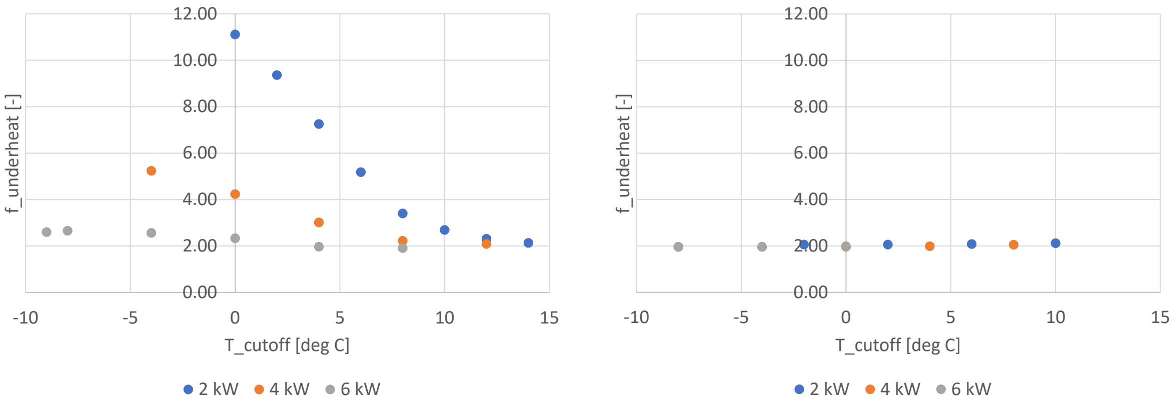
As has been explained in Section 3.3.2, the hybrid heat pump can operate in two modes: bivalent alternative or bivalent parallel. Therefore, not only has to be decided what heat pump capacity to use, but also what operation mode to use and with which switching temperatures. The capacity of the gas boiler is constant in the hybrid heat pump cases and equal to the capacity in the mono-gas boiler case (see Section 3.3.2).

Figure 5.3a displays the underheating f-factor for different heat pump capacities, across a range of cut-off temperatures. A decreasing trend can be seen in the f-factor with increasing $T_{cut\text{-}off}$. This can be expected as the ASHP has a lower performance with colder outside temperatures, so if the heat pump is switched on at lower temperatures, it is more likely that it cannot adequately heat the building, thus increasing the f-factor. This downward trend flattens off at higher cut-off temperatures which is because the heat demanded by the building is lower with increasing temperatures. It can also be seen that the effect of a changing $T_{cut\text{-}off}$ on the f-factor is lowered for increasing heat pump capacities, as the heat pump becomes able to supply more heat to the building with increasing capacity. Figure 5.3a only displays the results for the current insulation level. A complete overview of the results can be found in Appendix D.1.2.

The trends that are visible in Figure 5.3a can also be found for the other studied insulation levels. The f-factors did decrease with increasing insulation levels, and the $T_{cut\text{-}off}$ with acceptable f-factors decreased as well with increasing insulation levels.

Figure 5.3b depicts the same results but then for the bivalent parallel operation mode. It can be seen that the f-factors with this operation mode are much more stable when changing the cut-off temperature. As has been explained in Section 3.3.2, the bivalent temperature is different from the cut-off temperature in the bivalent parallel operation mode. The bivalent temperature for the 2 kW case was 14 °C, for the 4 kW case it was 12 °C and for the 6 kW case it was 4 °C.

There are two main reasons why the parallel operation mode is much more stable in supplying adequate heating than the alternative operation mode. First, in the region where both the heat pump and the gas boiler are on (i.e., outside temperatures between $T_{cut\text{-}off}$ and T_{biv}), the gas boiler will ensure adequate heat supply as its performance is not affected by the outside temperature. The second reason addresses

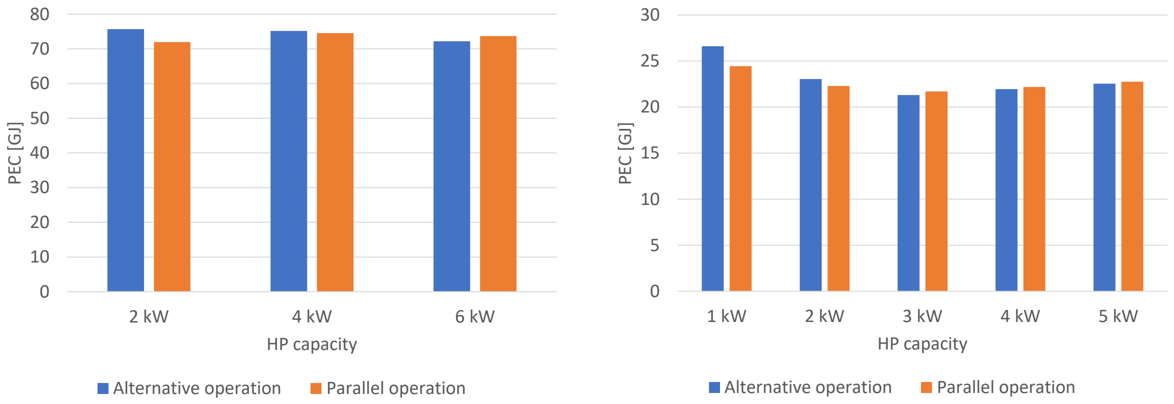


(a) Bivalent alternative operation

(b) Bivalent parallel operation

Figure 5.3: f-factor for underheating for current insulation level with a HHP with different heat pump capacities, for different cut-off temperatures

a limitation in the simulation model, which is in the heat pump component of the TRNSYS model. The heat pump component instantly works at full capacity when it is switched on, when in reality, heat pumps take some time to reach steady state conditions. Up to that moment the heat pump operates at a COP that is 50 % lower than in steady state conditions. This start-up phase lasts about two minutes[2] (Bagarella et al., 2016b). Because the heat pump in the TRNSYS model is able to instantly provide heat to the building, the f-factor is reduced. In the bivalent alternative mode, this effect can not be seen as it is compensated by the loss of heating capacity due to the colder outside air, but in the bivalent parallel mode, the gas boiler ensures adequate heating. More details on the heat pump component used in the TRNSYS model can be found in Appendix B.7.2.



(a) Current insulation level

(b) High insulation level

Figure 5.4: Yearly primary energy consumption of a hybrid heat pump with different heat pump capacities, for the current and high insulation level

By comparing the primary energy consumption of the tested cases, the combination of heat pump capacity and switching temperatures was found for both operation modes separately, that consumes the lowest primary energy. Figure 5.4 shows that for both the lowest and highest insulation levels, the differences between the alternative and parallel operation modes were relatively small. What can be noted is that for the lower heat pump capacities, the alternative operation mode results in the highest primary energy use in most cases while the opposite holds for the higher heat pump capacities.

For each insulation level, the combination of heat pump capacity and switching temperatures was chosen

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[2] According to Bagarella, Lazzarin, and Noro (2016b), this strong reduction of the COP of the heat pump during start-up is caused by the use of a thermostatic expansion valve in the heat pump. However, Bagarella, Lazzarin, and Lamanna (2013) state that these losses can be reduced if this valve is replaced by an electronic expansion valve.

that resulted in the lowest primary energy consumption. These results are displayed in Table 5.2.

Table 5.2: Chosen HHP system set-up for the studied insulation levels

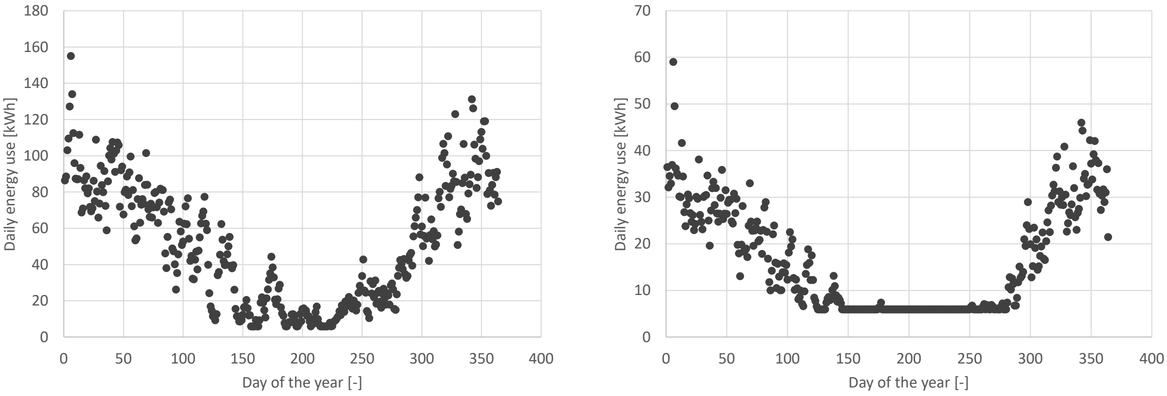
Insulation level	HP capacity [kW]	$T_{cut\text{-}off}$ [°C]	T_{biv} [°C]	Operation mode
Current	2	2	14	Alternative
Improved - HT radiators	5	-8	0	Parallel
Improved - LT radiators	5	-8	0	Parallel
High	3	-4	-4	Alternative

5.3 The present-day techno-economic results

In this section, the present-day techno-economic results will be presented. These analyses use the values for 2018 with regard to CO_2 intensities, pricing and primary energy factors, which were presented in Section 3.4 of the methods. The results are structured around the three studied heat sources. A complete overview, with the results from all three models next to each other, can be found in Appendix C.3.

5.3.1 Natural gas boiler

Table 5.3 displays the techno-economic results of the natural gas boiler model, for the three insulation levels. All studied insulation levels use high temperature radiators. Firstly, it can be noted that the DHW primary energy consumption and DHW gas use are equal in all cases, as the usage profile and production source is equal in all studied insulation levels. As expected, the gas use for space heating decreases with increased insulation, and therefore also the primary energy consumption, the CO_2 emissions and energy costs also decrease. Figure 5.5 depicts the daily energy use for space heating and DHW production over a whole year. It can be seen that there is a significant difference in the scale of energy consumption when comparing the current insulation level with the high insulation level. What can also be seen is that the high insulation level has no space heating demand during a large period in the middle of the year, only DHW demand, therefore Figure 5.4b shows a constant line over this period, while the current insulation level does have some space heating demand over this period.



(a) Current insulation level

(b) High insulation level

Figure 5.5: Daily energy used by space heating and DHW production over a year, expressed in kWh, for both the current and high insulation levels

A non-discounted payback time was calculated for the two higher insulation levels, in comparison to the current insulation level. As the system setup is equal in all cases, this payback time represents the payback time for the extra added insulation, which is around 22 years for both cases.

Table 5.3: Present-day techno-economic overview of natural gas boiler system

		Gas boiler		
	Insulation level:	Current	Improved - HT rad	High
System setup				
Gas boiler capacity	[kW]	19.5	19.5	19.5
Energetic factors				
PEC DHW	[GJ]	9	9	9
PEC Space heating	[GJ]	67	37	16
Total PEC	[GJ]	76	46	25
Gas use for DHW	[m^3]	222	222	222
Gas use for space heating	[m^3]	1661	910	390
Total gas use	[m^3]	1883	1132	612
Environmental factors				
GHG emissions gas	[kg CO$_2$]	3740	2248	1215
Economic factors				
Investment costs heat source	[€]	979	979	979
Investment costs insulation and heat emitters	[€]	0	8980	19746
Yearly total energy costs	[€]	1262	758	410
(Non-discounted) Pay Back Time	[years]		20	24

5.3.2 Hybrid heat pump

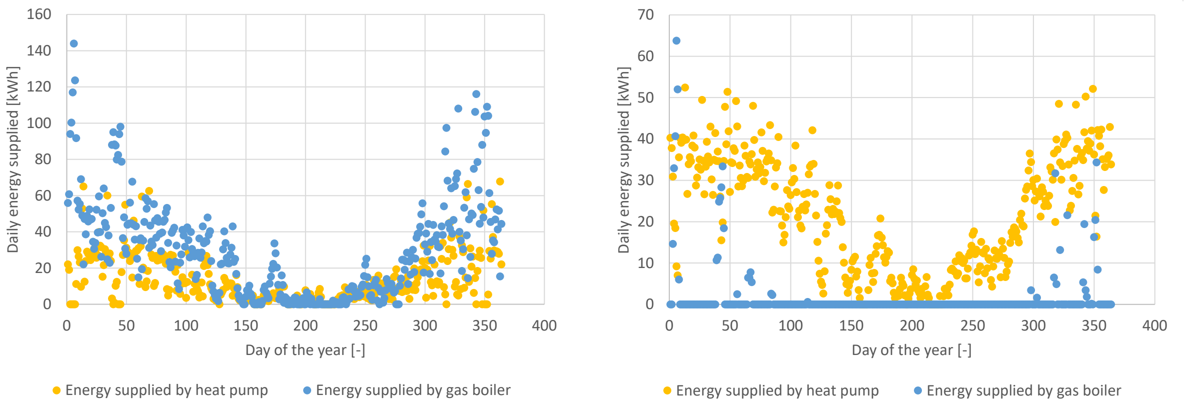
Table 5.4 displays the techno-economic results of the hybrid heat pump model, for the three insulation levels. However, a diversification has been made by modelling the improved insulation level with both HT- and LT- radiators. Because the hybrid heat pump uses only the gas boiler for DHW production, the results for the DHW production are equal to those of the gas boiler model. It can be seen that the PEC for space heating decreases with increased insulation.

When looking at the performance indicators of the heat pump, it can be seen that the SPF does not increase with increasing insulation in all cases, just as the load factor that does not increase with increasing insulation in all cases. This is not what was expected, although it can be explained by addressing a limitation in the method with which the heat pump capacity and operation mode were chosen in the previous section. This limitation will be explained next.

When switching from the current insulation level to the improved insulation level with HT-radiators, the capacity and more importantly, the operation strategy (i.e., $\mathrm{T_{cut\text{-}off}}$ and $\mathrm{T_{biv}}$) change as well. Because the heat pump is operating at lower temperatures in the improved insulation case, the COP of the heat pump at those temperatures is also lower. Therefore, the SPF of the heat pump in the improved insulation case with HT-radiators is lower than the current insulation case. The lower load factor of the improved insulation case with LT-radiators compared to the improved insulation case with HT-radiators can be explained by the f-factor criteria that is used when choosing the heat pump capacity. Because there is only a maximum criteria for the f-factor (i.e., $f_{HHP} < (1+\alpha) \cdot f_{mono\text{-}gas}$), it is possible that the HHP models were operating with a lower f-factor than the mono-gas boiler models. This means that the building is heated more adequately with the HHP than in the case with the mono-gas boiler. In the improved-HT case, the f-factor is 1.85, while in the improved-LT case, the f-factor is 1.67. Thus, in the improved-LT case, more heat is supplied to the building than in the improved-HT case. This heat is supplied by the gas boiler, thus lowering the load factor for the improved-LT case. This indicates a limitation in the method for choosing the heat pump capacity and operation mode. Instead of setting a maximum criteria for the f-factor, it might be better to make sure the f-factor is equal to the reference case of the gas boiler only model (i.e., $f_{HHP} = f_{mono\text{-}gas}$).

Still, a clear trend is visible of increasing SPFs and load factors for increasing insulation levels (see Table 5.4). For the high insulation level, almost all of the space heating demand is covered by the heat pump. Also, for this insulation level the DHW uses more energy than the space heating.

Figure 5.6 illustrates the difference in load factor between the current insulation level and the improved



(a) Current insulation level

(b) Improved insulation level with HT radiators

Figure 5.6: Daily energy supplied for space heating over a year, expressed in kWh, for both the current and improved-HT insulation levels

insulation levels with HT radiators. In the second case, the gas boiler only supplies space heating in cold winter days, while the gas boiler provides space heating over a much wider time frame in the current insulation case. However, on these cold winter days, the amount of heat supplied by the gas boiler is significant for both insulation cases. It should be noted that Figure 5.6 does not include DHW production.

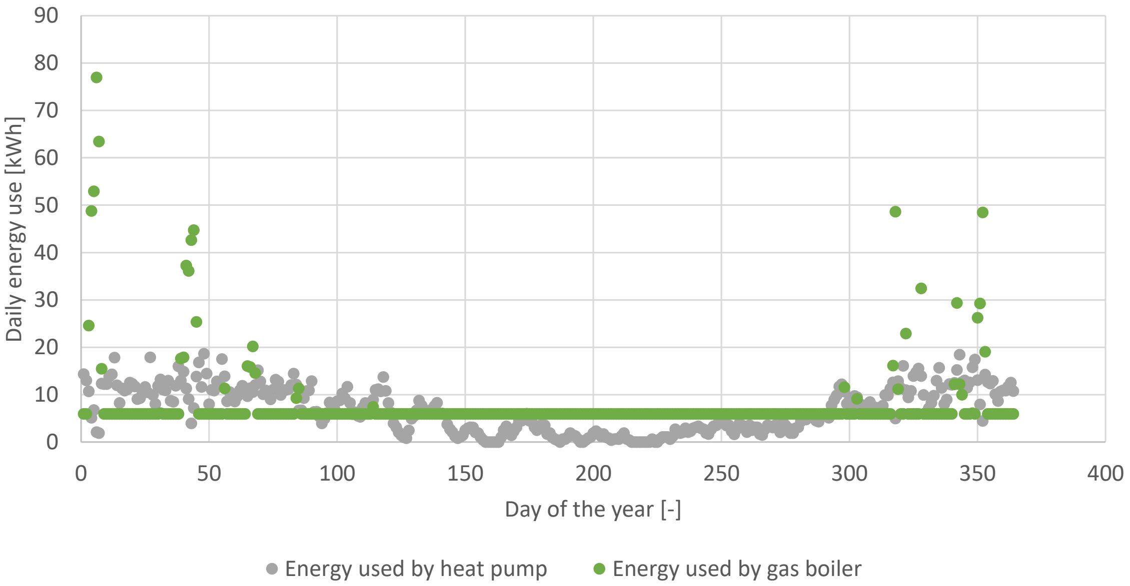


Figure 5.7: Daily energy used for space heating and DHW production over a year, produced by a HHP for the improved insulation level with LT radiators

Figure 5.7 shows the energy used by the heat pump and gas boiler in the HHP system for the improved insulation case with LT radiators. It can be seen that the gas boiler primarily supplies DHW over the year, indicated by the constant line in the graph. However, during the cold winter days, the gas boiler is required and uses much more energy than the heat pump does on average over the year.

When looking at the environmental factors in Table 5.4, the GHG emissions decrease with increasing insulation levels. Because the energy costs for the hybrid heat pump system in the current insulation level are higher than that of the gas boiler system in the same insulation level, no payback time can be calculated, resulting in a negative value. For the improved and high insulation cases, the payback time is around 33 years.

Table 5.4: Present-day techno-economic overview of hybrid heat pump system

		Hybrid heat pump			
	Insulation level:	Current	Improved - HT rad	Improved - LT rad	High
System setup					
Gas boiler capacity	[kW]	19.5	19.5	19.5	19.5
ASHP capacity (A2/W35)	[kW]	2	4	4	3
T_{cutoff}	[°C]	2	-8	-8	-4
T_{biv}	[°C]	14	0	0	-4
Energetic factors					
PEC DHW	[GJ]	9	9	9	9
PEC Space heating	[GJ]	63	32	25	12
Total PEC	[GJ]	72	41	34	21
SPF	[-]	2.66	2.40	3.15	3.19
Load factor	[-]	0.32	0.93	0.92	0.99
Gas use for DHW	[m^3]	222	222	222	222
Gas use for space heating	[m^3]	1141	63	75	6
Total gas use	[m^3]	1363	285	297	228
Electricity use for space heating	[kWh]	1876	3265	2471	1343
Energy use for DHW in kWh	[kWh]	2169	2169	2169	2169
Energy use for space heating in kWh	[kWh]	13023	3880	3207	1402
Total energy use in kWh	[kWh]	15192	6049	5375	3570
Environmental factors					
GHG emissions gas	[kg CO_2]	2707	565	590	453
GHG emissions electricity	[kg CO_2]	918	1599	1210	658
GHG emissions	[kg CO_2]	3625	2164	1800	1111
Economic factors					
Investment costs heat source	[€]	3379	3579	3579	1700
Investment costs insulation and heat emitters	[€]	0	8980	14942	25708
Energy costs gas	[€]	886	191	199	153
Energy costs electricity	[€]	413	686	519	282
Yearly total energy costs	[€]	1299	877	718	435
(Non-discounted) Pay Back Time	[years]	-74	33	34	33

5.3.3 All-electric ASHP

Table 5.5 depicts the techno-economic results of the all-electric air-source heat pump model, for the three insulation levels, including both types of radiators for the improved insulation level. It can be seen that for the upper two insulation levels, the DHW production requires more electricity (and therefore also primary energy) than the space heating system. The payback time for these studied cases is high. The yearly energy costs for the lower two insulation levels is higher than that of the gas boiler model with current insulation level (i.e., the reference case), resulting in a negative value for the pay back time. The SPF of the heat pump increases with increasing insulation levels.

The daily energy used by the all-electric system for space heating and DHW production over a year is depicted in Figure 5.8, for the high insulation case. It can be seen that for almost the whole year, the energy used for DHW is higher than the energy used for space heating, as both the blue and the orange dots display energy used for DHW (but from different sources) and should therefore be added. It can be striking to see that the energy used by the heat pump for DHW is lower during the summer than during the winter. In summer it even is lower than the energy consumed by the auxiliary electric heater. In reality, it might be beneficial to have more of the DHW demand covered by the heat pump than by the auxiliary heater in summer, as the heat pump can produce heat efficiently with warmer outside air. However, the operation strategy used for heating the DHW tank does not take into account the more efficient operation of the heat pump during summer. It uses the same temperature setpoints for switching between the auxiliary heater and the heat pump throughout the year (more information on the operation strategy can be found in Appendix B.9). This unveils a limitation of this operation strategy.

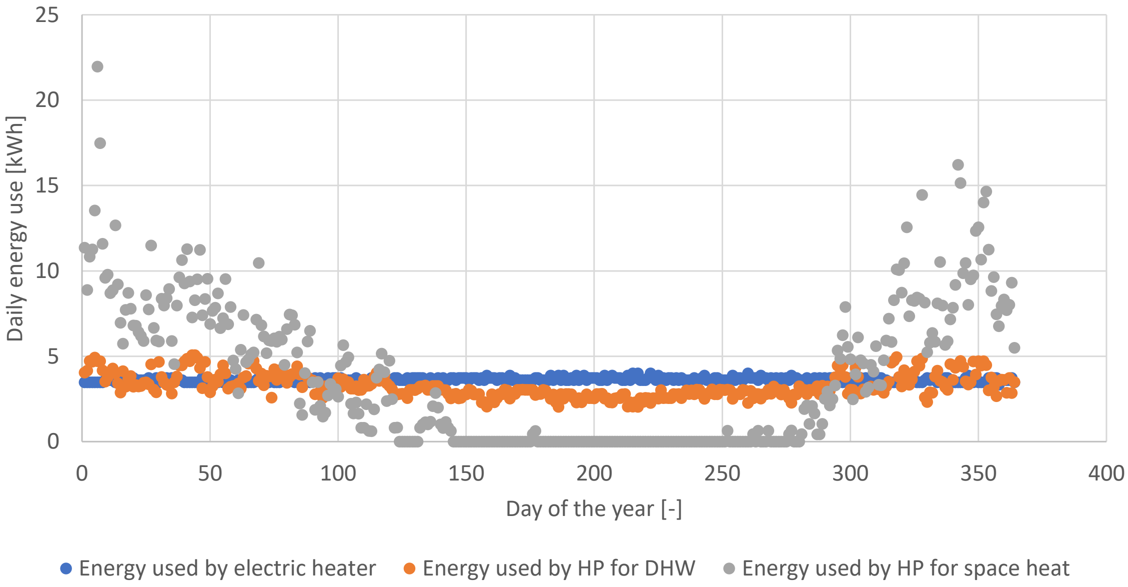


Figure 5.8: Daily energy used for space heating and DHW production over a year, produced by an all-electric system with an ASHP and a DHW storage tank with auxiliary heater, in a building with high insulation

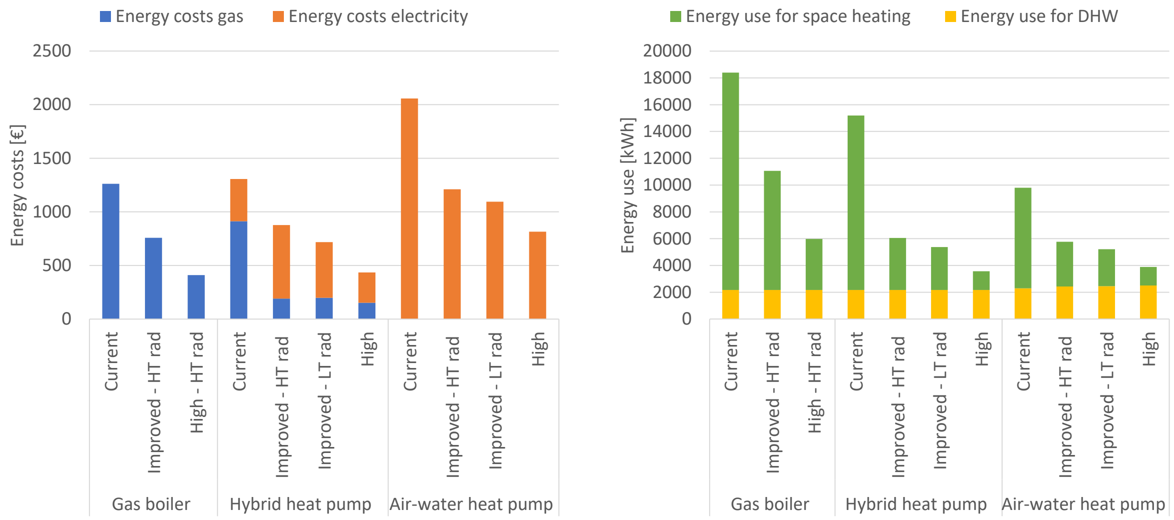
Table 5.5: Present-day techno-economic overview of the all-electric air-source heat pump system

		Air-water heat pump			
	Insulation level:	Current	Improved - HT rad	Improved - LT rad	High
System setup					
ASHP capacity (A2/W35)	[kW]	9	6	6	4
Energetic factors					
PEC DHW	[GJ]	21	22	22	23
PEC Space heating	[GJ]	68	30	25	12
Total PEC	[GJ]	88	52	47	35
SPF	[-]	2.02	2.17	2.63	2.74
Electricity use for DHW	[kWh]	2291	2430	2452	2508
Electricity use for space heating	[kWh]	7508	3337	2762	1376
Electricity use	[kWh]	9799	5767	5214	3884
Environmental factors					
GHG emissions electricity	[kg CO_2]	4789	2824	2557	1901
Economic factors					
Investment costs heat source	[€]	6275	5305	5305	5225
Investment costs insulation and heat emitters	[€]	0	8980	14942	25708
Yearly total energy costs	[€]	2058	1211	1095	816
(Non-discounted) Pay Back Time	[years]	-8	283	121	69

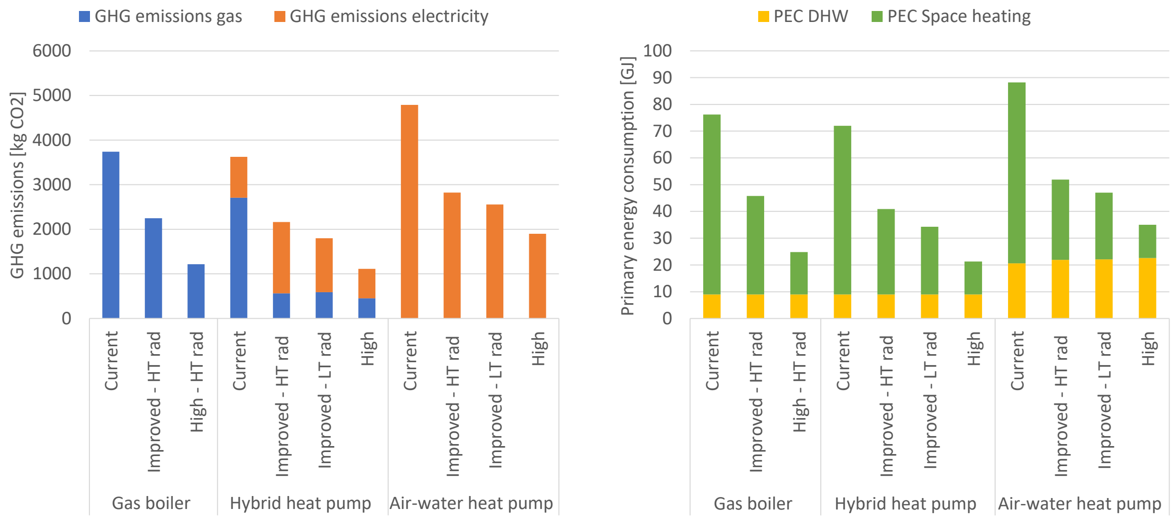
5.3.4 Comparing the three models

Figure 5.9 presents a comparison between the three discussed models on (primary) energy use, fuel costs and GHG emissions. In Figure 5.9b, the total energy consumed for DHW production and space heating is expressed in kWh. It can be seen that the hybrid and all-electric heat pump systems use considerably less energy than the gas boiler system. However, the differences between the two heat pump systems are small. In contrast, Figure 5.9d shows that the difference in terms of primary energy consumption between the hybrid heat pump system and gas boiler system is small while the all-electric system uses more primary energy due to the higher primary energy used for DHW production.

Figure 5.9a shows that the gas boiler system is the cheapest system in terms of energy costs. The all-electric system is the most expensive to operate while the hybrid system is in between these systems, in



(a) Yearly natural gas and electricity costs (b) Yearly energy use for DHW and space heating



(c) Yearly CO_2 emissions from natural gas and electricity (d) Yearly primary energy consumption

Figure 5.9: Energy use, energy cost, GHG emissions and PEC for the three heat sources and four insulation levels

terms of energy costs. This figure also displays how switching to an all-electric system without investing in insulation will result in significantly higher energy costs.

The amount CO_2 emitted per year is displayed in Figure 5.9c. It can be seen that with the current CO_2 intensity of the Dutch electricity mix, both the hybrid and all-electric heat pump systems result in higher GHG emissions.

Figure 5.10 compares the hybrid heat pump system to the all-electric air-source heat pump system in terms of the seasonal performance factor (SPF). It can be seen that the heat pump in the hybrid set-up operates at higher SPFs for all considered insulation cases. This is probably due to the fact that the heat pump in the all-electric system has to operate also at the lowest temperatures and also has to produce heat for the DHW production.

Furthermore, the graphs displaying the energy supplied and used over the whole year for all studied heat sources and insulation levels, similar to the figures displayed in this chapter, can be found in Appendix D.2.

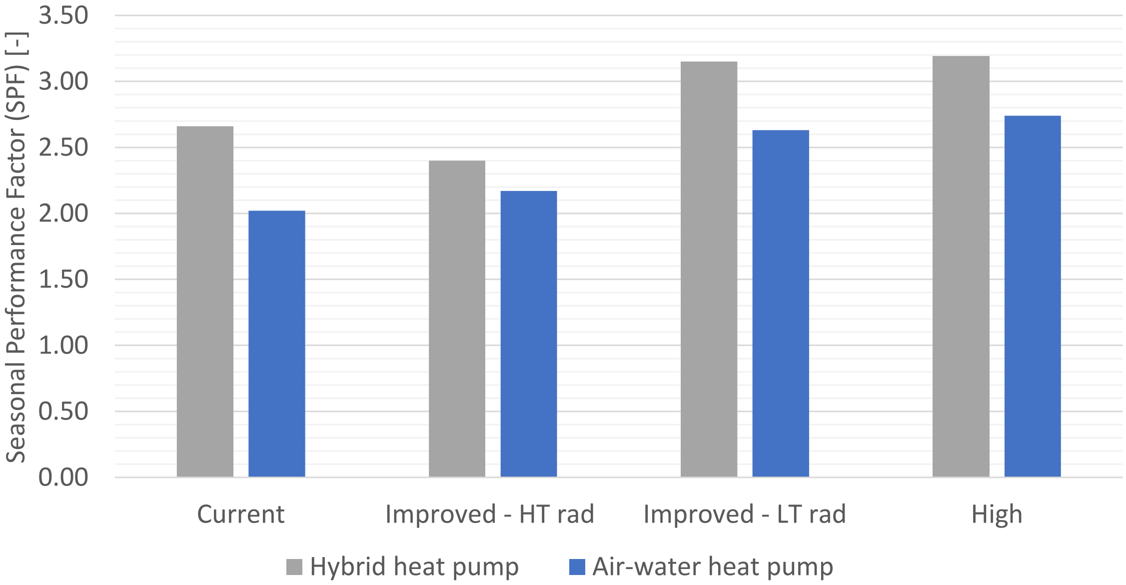


Figure 5.10: Comparison of the Seasonal Performance Indicator (SPF) of the hybrid heat pump and all-electric heat pump system, for the four considered insulation and heat emitter levels

Chapter 6

Techno-economic analysis of the scenarios

To create insight into what the techno-economic impact of the scenarios are within the time frame considered in this study (i.e,. from 2018 to 2050), the present-day techno-economic assessment of the previous chapter will be expanded to include yearly assessments for each year until 2050.

As there are many design options (i.e., 26 in total), it is not possible to deal with all of them in detail. The design options with the highest and lowest insulation will be highlighted to indicate the range of possible results for each scenario. Furthermore, the 'preferred' design option will firstly be addressed from the perspective of the home-owner, in which the goal is to minimize the yearly total costs in 2025 and 2040 and secondly from the perspective of the policy maker, in which the goal is to have the lowest amount of CO_2 emissions at the lowest costs, which is indicated by the carbon reduction costs. The complete results, including all design options, can be found in Appendix F.1. The design options, which have been introduced in Section 3.5.5, will be referred to with their corresponding 'codes'. These can be found in Appendix C.2.

To calculate the carbon reduction cost, it is necessary to know what the CO_2 emissions will be if no insulation is applied and only natural gas is used to supply space heating and DHW. This will be the reference or 'business as usual' case with which the carbon reduction cost is calculated. For this reference case, the total CO_2 emission between 2018 and 2050 is 124 tonnes. The development of the yearly total costs for this case is displayed in Figure 6.1. The summed total of the yearly costs is 62 thousand €.

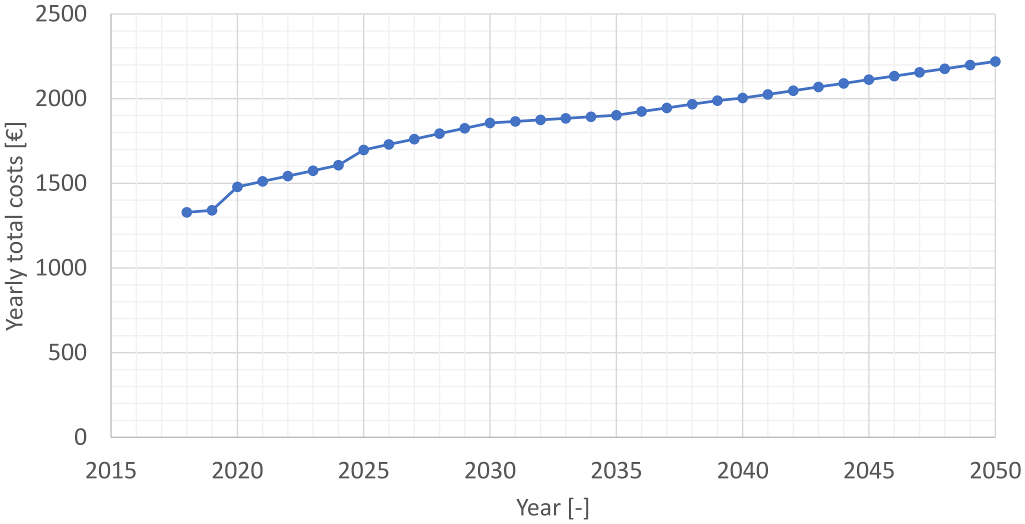


Figure 6.1: Yearly total costs of the reference or 'business as usual' case

6.1 Hybrid heat pump as stepping stone to all-electric (S1)

For this scenario, S1f was the design option where no insulation was applied. As can be seen in Table 6.1, this resulted in the highest costs as well as the highest CO_2 emissions. Therefore, the carbon reduction cost of this design option was the highest of all studied options for this scenario. When looking at this design option in terms of yearly costs, Figure 6.2 shows that this design option also results in the highest yearly costs over the whole studied period.

Table 6.1: Main results in terms of costs and CO_2 emissions for the design options studied in S1

		S1a	S1b	S1c	S1d	S1e	S1f
Yearly costs summed	[thousand €]	56	59	65	60	64	70
Total CO_2 emissions	[tonnes]	42	37	66	44	67	69
Carbon reduction cost	[€/kg]	0.7	0.7	1.1	0.8	1.1	1.3

Design option S1b was the option with the highest insulation level applied at the first natural switching moment. Table 6.1 shows that this resulted in the lowest costs and the lowest CO_2 emissions, resulting in the lowest carbon reduction costs. S1a resulted in a similar carbon reduction cost but with higher CO_2 emissions and the carbon reduction cost of S1d is close (i.e., both options switch to improved insulation level in 2025, with S1a applying LT heat emission in 2025 and S1d in 2040). Figure 6.2 shows that S1a offers the lowest path in terms of yearly costs between 2025 and 2040, and the second lowest after 2040. S1b and S1d on the other hand, involve a significantly higher yearly cost.

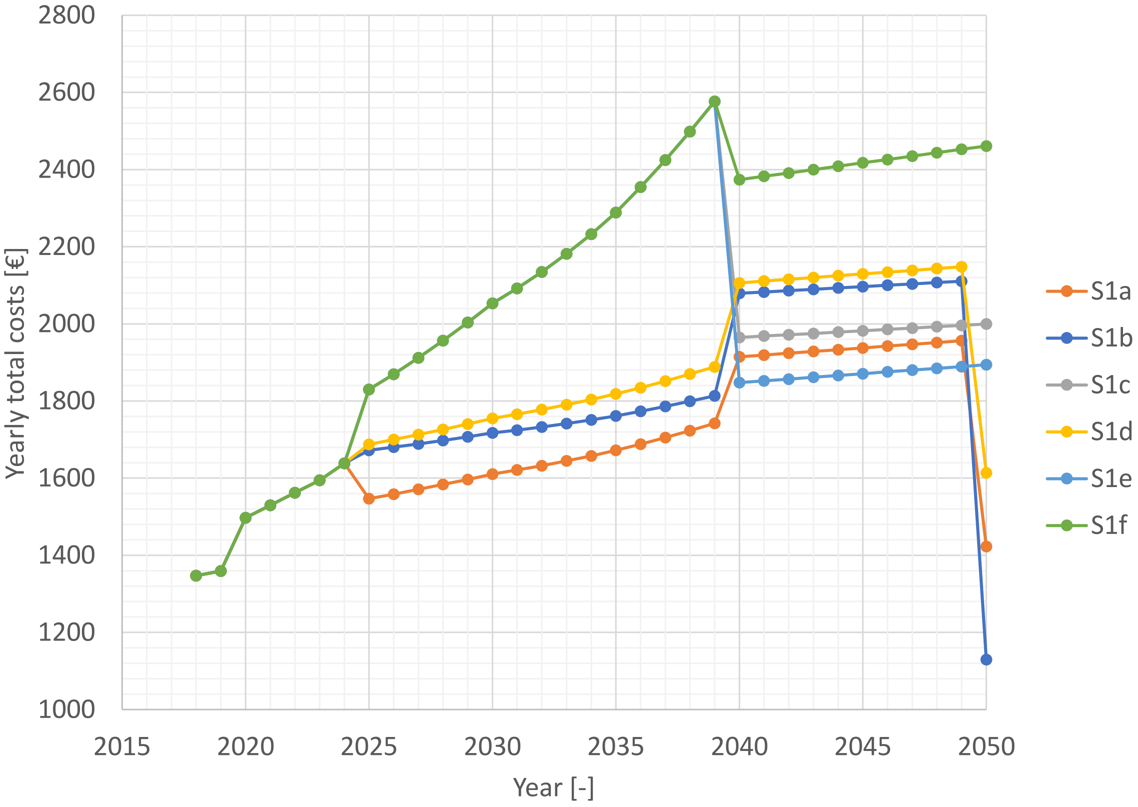


Figure 6.2: Yearly total costs of the six considered design options for the first scenario

6.2 Hybrid heat pump as end-solution with green gas (S2)

Similarly to S1, in the second scenario the design option with the highest insulation applied at the first moment, S2h, results in the lowest CO_2 emissions, while the design option with no insulation applied, S2g, has the highest costs and CO_2 emissions. Table 6.2 shows that in terms of carbon reduction costs, the scenarios that insulate to the improved level in 2025 (i.e., S2d, S2e and S2f) are close to the highest insulation design option, by emitting more CO_2 but also requiring lower costs. The scenarios that wait with applying building adaptations until 2040 (i.e., S2a, S2b and S2c) also have similar carbon reduction costs, with respect to each other.

Table 6.2: Main results in terms of costs and CO_2 emissions for the design options studied in S2

		S2a	S2b	S2c	S2d	S2e	S2f	S2g	S2h
Yearly costs summed	[thousand €]	61	62	62	53	54	55	77	56
Total CO_2 emissions	[tonnes]	67	68	68	45	45	43	75	37
Carbon reduction cost	[€/kg]	1.1	1.1	1.1	0.7	0.7	0.7	1.6	0.6

When looking at the total yearly costs displayed in Figure 6.3, a clear difference can be seen between the design options that insulate in 2025 and with those who do not. However, it can also be seen that when looking at the yearly total costs from 2025 onwards, design option S2d and S2e result in the lowest costs (i.e., both apply the improved insulation level in 2025, S2e switches to low temperature heat emission in 2040). After 2040, all design options that have applied insulation result in relatively similar yearly total costs, but S2d has a slightly lower cost than S2e.

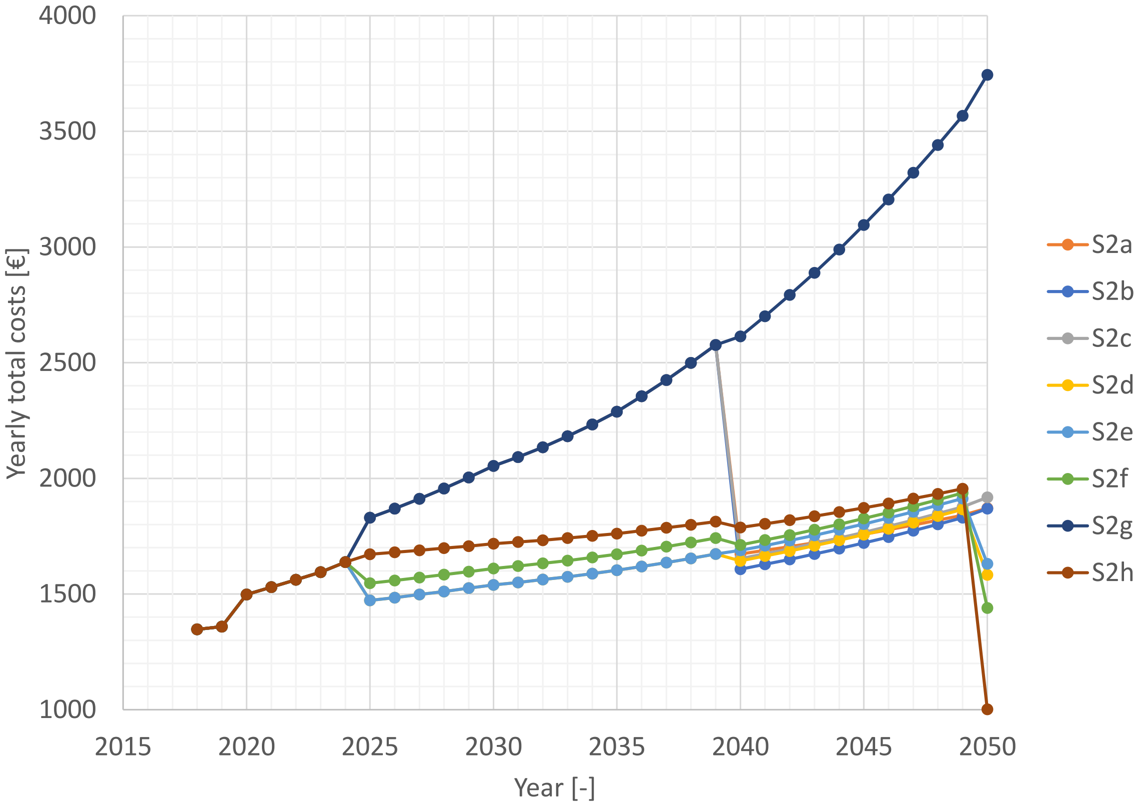


Figure 6.3: Yearly total costs of the six considered design options for the second scenario

6.3 Full and immediate shift to all-electric (S3)

Table 6.3 shows that the lowest carbon reduction cost in the third scenario is present when applying design option S3a, although S3b does result in lower CO_2 emissions. Design option S3a applies the improved insulation level in 2025 while S3b applies the high insulation level. Both also install low temperature radiators in 2025. Design option S3c results in the highest costs and CO_2 emissions as no building adaptations are applied at this option. Figure 6.4 shows that S3a offers the lowest yearly total costs for the home owner.

Table 6.3: Main results in terms of costs and CO_2 emissions for the design options studied in S3

		S3a	S3b	S3c
Yearly costs summed	[thousand €]	60	65	73
Total CO_2 emissions	[tonnes]	42	38	56
Carbon reduction cost	[€/kg]	0.7	0.8	1.1

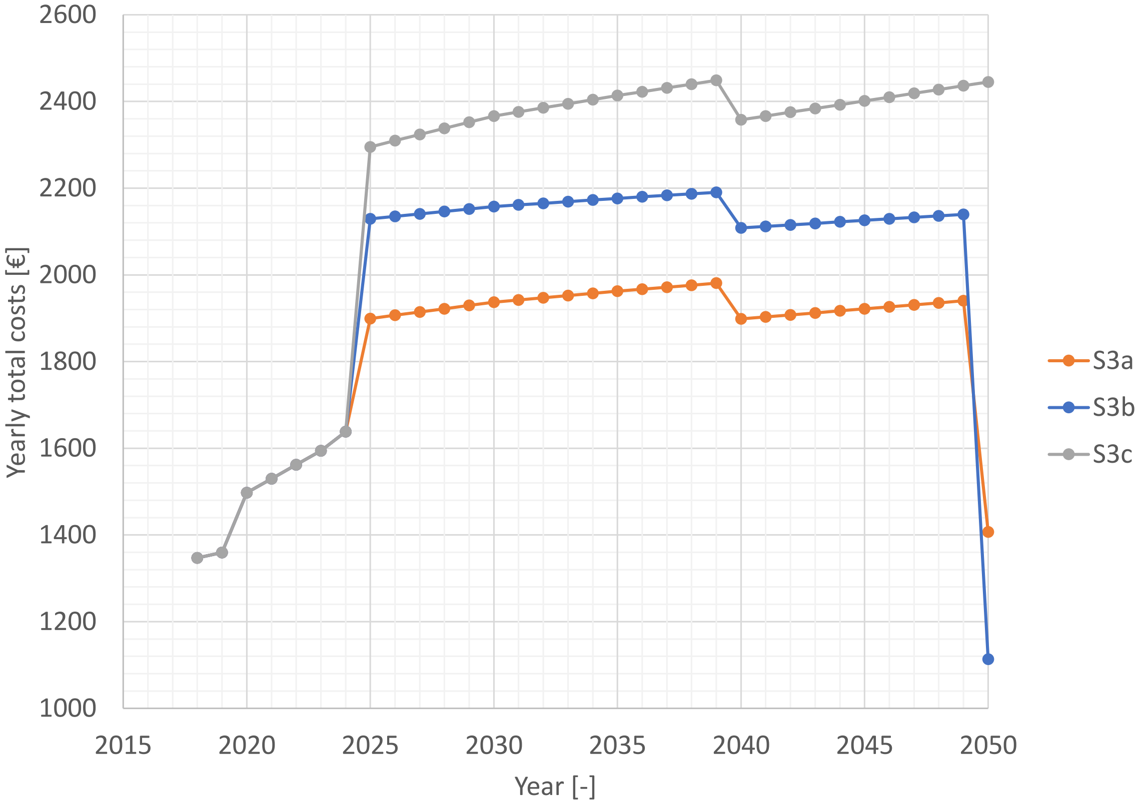


Figure 6.4: Yearly total costs of the six considered design options for the third scenario

6.4 Postponed decision to switch to all-electric or green gas (S4)

As described in Chapter 4, the heat source installed in 2040 for the fourth scenario can be either an air-source heat pump or another gas boiler. The results of these two options will first be dealt with separately.

For the design options that end up with an all-electric system with an ASHP in 2040, the option where no insulation is applied, S4f, results in the highest carbon reduction cost while the option that applies high insulation in 2025, S4g, results in the lowest carbon reduction cost. This can be seen in Table 6.4. When looking at the yearly total costs displayed for the ASHP options in Figure 6.5, it can be seen that the lowest costs are present at S4g, but after 2040, S4i offers lower costs (i.e., in S4i the improved insulation level is applied in 2025 and in 2040 low temperature radiators are installed). Referring back to Table 6.4, it can be seen that this design option also offers a carbon reduction cost that is slightly higher than that of S4g.

Table 6.4: Main results in terms of costs and CO_2 emissions for the design options studied in S4

Heat source in 2040:		ASHP				Gas boiler				
		S4a	S4f	S4g	S4i	S4b	S4c	S4d	S4e	S4h
Yearly costs summed	[thousand €]	65	70	55	56	65	70	82	54	62
Total CO_2 emissions	[tonnes]	74	77	43	56	77	80	85	45	62
Carbon reduction cost	[€/kg]	1.3	1.5	0.7	0.8	1.4	1.6	2.1	0.7	1.0

For the design options that stick with a gas boiler system in 2040, Table 6.4 shows similar results with the highest insulation design option, S4e, resulting in the lowest carbon reduction cost while the design option that does not apply insulation, S4d, results in the highest carbon reduction costs. Figure 6.5 shows that S4e also offers the lowest yearly total costs for the home owner.

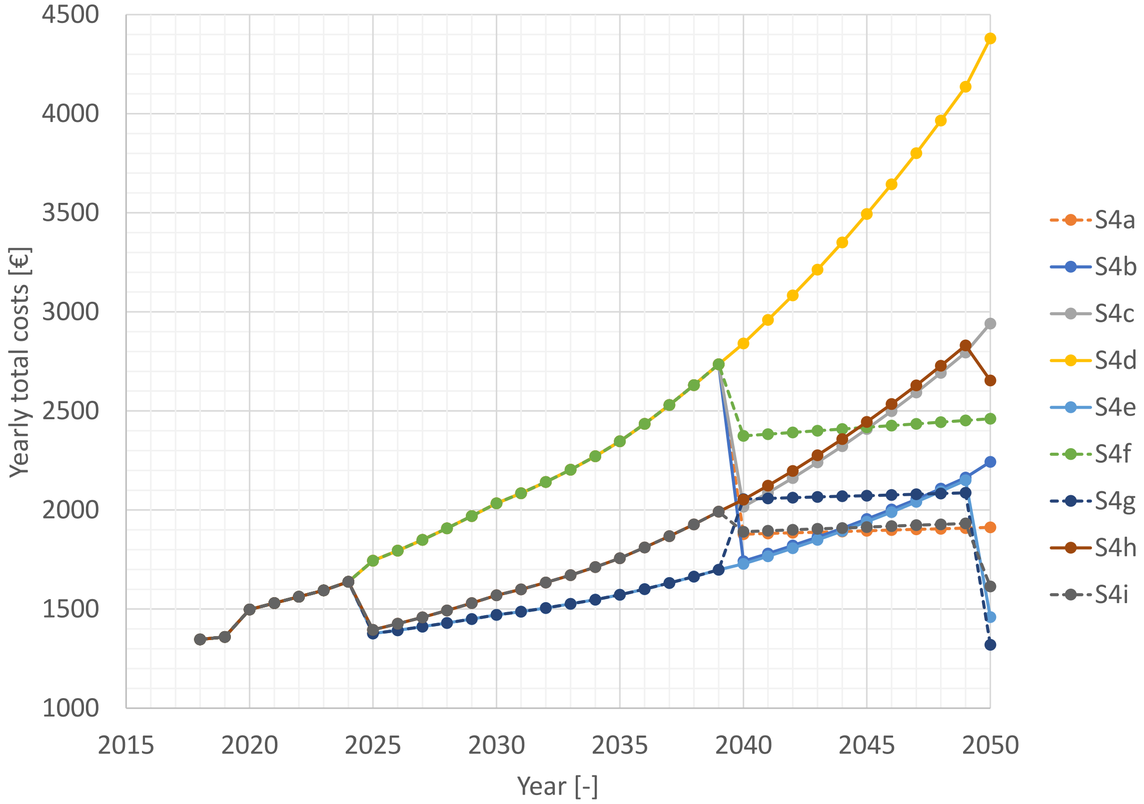


Figure 6.5: Yearly total costs of the six considered design options for the fourth scenario. The design options with the dashed lines end up with an ASHP in 2040 while those with solid lines keep the gas boiler.

When comparing the options that end up with an ASHP to the options that stick with the gas boiler, it can be seen that for both cases the design option with the lowest carbon reduction cost (i.e., S4g and S4e) has a value of 0.7 €/kg. However, the gas boiler option results in slightly higher CO_2 emissions. It can also be seen that the carbon reduction costs of the gas boiler options have a larger variation than the ASHP options.

In terms of yearly total costs, both options are equal (in case of equal insulation levels) up to 2040.

From 2040 to 2048, the green gas options result in lower yearly total costs, but after 2048 the ASHP option results in lower costs. It should be noted that the ASHP options switch to a low temperature heat emission system while the gas boiler options do not.

6.5 The four scenarios compared

Table 6.5 compares the design options with the lowest and highest insulation levels for all four scenarios, in terms of carbon reduction costs. For the first, second and fourth scenarios, the lowest carbon reduction costs resulted from the design option with the highest insulation level and vice versa. For the third scenario, the design option that applies improved insulation in 2025 results in a carbon reduction cost that is slightly lower than the design option with the highest insulation (i.e., 0.02 €/kg). What is also noteworthy when looking at the third scenario, is that the difference between the highest and lowest insulation design options is the smallest, compared to the other scenarios. Thus, insulation has the lowest impact on the carbon reduction in the third scenario, compared to the others. A possible explanation for this is the different price development of electricity, which is relatively stable (see Figure 3.6a), compared to the price development of the gas mix, which is increasing steadily (see Figure 3.9b). Therefore, reducing the energy demand through insulation has a larger impact on the scenarios that use gas for space heating and DHW than on the third scenario, that switches to an all-electric system.

Table 6.5: Range of carbon reduction costs for the design options with the highest and lowest insulation level, for all four scenarios

		S1	S2	S3	S4 (ASHP)	S4 (gas boiler)
Design option with highest insulation	[€/kg]	0.7	0.7	0.8	0.7	0.7
Design option with lowest insulation	[€/kg]	1.3	1.6	1.1	1.5	2.2

Table 6.5 also shows that the range in the carbon reduction cost of the design options in the fourth scenario that switch to an all-electric system is more narrow than the range of the design options in the fourth scenarios that keep the gas boiler system.

Table 6.6 compares the design options that are preferred from the perspective of the home-owner (i.e., with the lowest yearly total costs at the natural switching moments) for each of the four scenarios. When looking at the discounted total costs, it can be seen that there is a relatively small difference between the four scenarios, where the second scenario has the lowest costs and the third the highest. It is interesting to compare these costs with the discounted total costs of the business as usual reference case, which was 39 thousand €. All four scenarios are thus close to the reference case in terms of discounted costs.

Table 6.6: 'Preferred' design option (from the perspective of a home-owner) of each scenario compared in terms of costs and environmental impact

		S1a	S2d	S3a	S4e
Total investment costs	[thousand €]	22	16	23	21
Total energy costs	[thousand €]	35	38	38	33
Discounted total costs	[thousand €]	40	38	41	40
Total yearly costs in 2025	[€]	1550	1470	1900	1380
Total yearly costs in 2040	[€]	1910	1640	1900	1730
Yearly costs summed	[thousand €]	56	53	60	54
Primary energy use	[GJ]	800	850	750	920
CO_2 emissions electricity	[tonnes]	9	10	16	0
CO_2 emissions gas	[tonnes]	33	35	26	45
Total CO_2 emissions	[tonnes]	42	45	42	45
Carbon reduction cost	[€/kg]	0.7	0.7	0.7	0.7

When looking at the total yearly costs in 2025, it can be seen that the fourth scenario results in the lowest costs and the third in the highest costs. The first and second scenarios are close to each other, which can be expected because the only difference between these two is that the first scenario installs low temperature radiators in 2025 while the second keeps the high temperature radiators. Figure 6.6 shows that in 2040, the yearly costs of the four scenarios are closer together. Table 6.6 depicts the results of the sum of these yearly costs over the whole considered period. It can be seen that the third scenario results in the highest costs while the other scenarios result in somewhat lower costs. The summed yearly costs of the business as usual reference case is higher than all four considered scenarios with an amount of 61 thousand €.

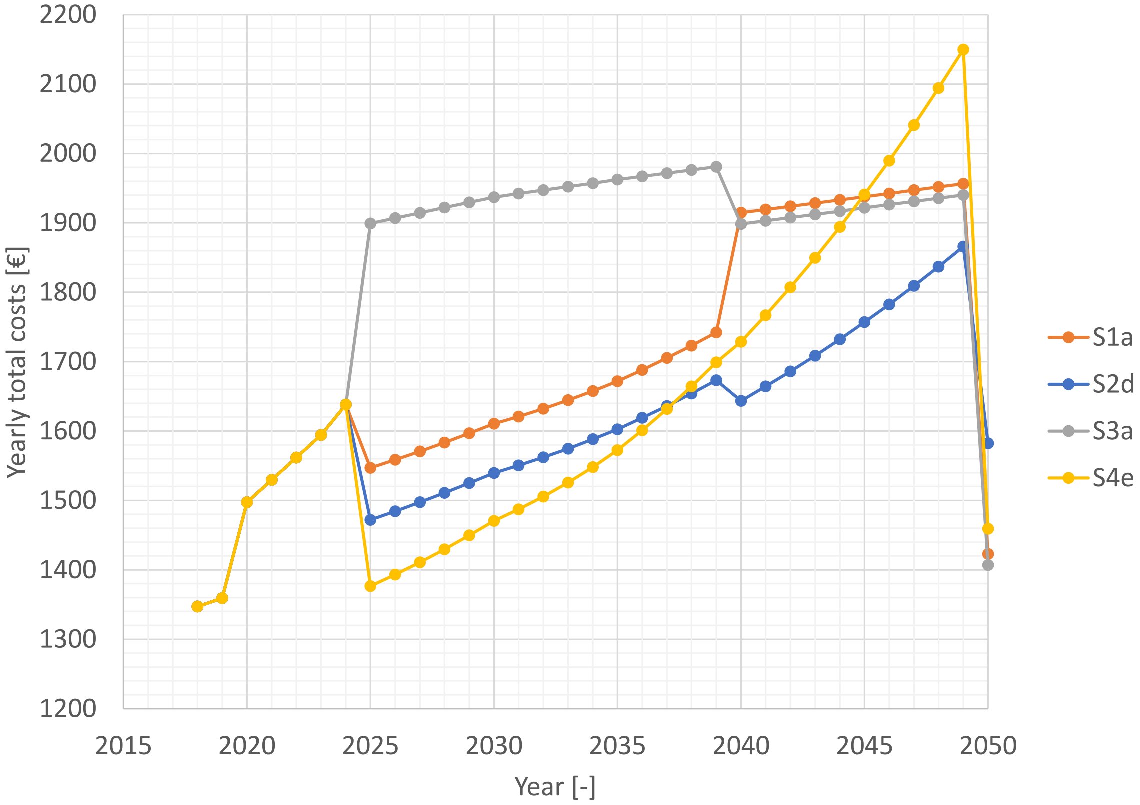


Figure 6.6: 'Preferred' design option (from the perspective of a home-owner) of each scenario compared in terms of yearly costs

Table 6.6 also shows that even though the third scenario results in the highest sum of yearly costs, it also results in the least use of primary energy while the fourth scenario uses the most. Figure 6.7 shows that, in terms of CO_2 emissions, the four scenarios follow similar paths and that the yearly CO_2 emitted before any building adaptations or change in heat source are implemented (i.e., before 2025) is much higher. In fact, in this period before 2025, 26 tonnes of CO_2 is emitted[1], which is very significant as the total CO_2 emissions over the whole period are between 42 and 45 tonnes for the four scenarios.

Table 6.6 shows that the least CO_2 is emitted by the first and third scenarios but that the differences are relatively small. From the perspective of the policy maker, a preferred scenario is not very apparent as the carbon reduction cost of all four scenarios are all around 0.7 €/kg. Recalling that the total CO_2 emissions of the business as usual reference case were 124 tonnes and that the total discounted costs as well as the summed yearly costs were similar to the studied scenarios, it can be stated that the four design options that are preferred by the home-owner are similarly effective at reducing the CO_2 emissions at a low cost, which is important from the perspective of a policy maker.

If the preferred design options were not chosen from the perspective from a home-owner (which is the case in the design options of Table 6.6 and Figures 6.6 and 6.7), but from the perspective of a policy maker, the goal would be to minimize the CO_2 emissions at the lowest (carbon reduction) cost. If this preference

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[1] This can be seen in Table 6.6 at the CO_2 emissions from gas for the third scenario, as this scenario only uses electricity for space heating and DHW production after 2025.

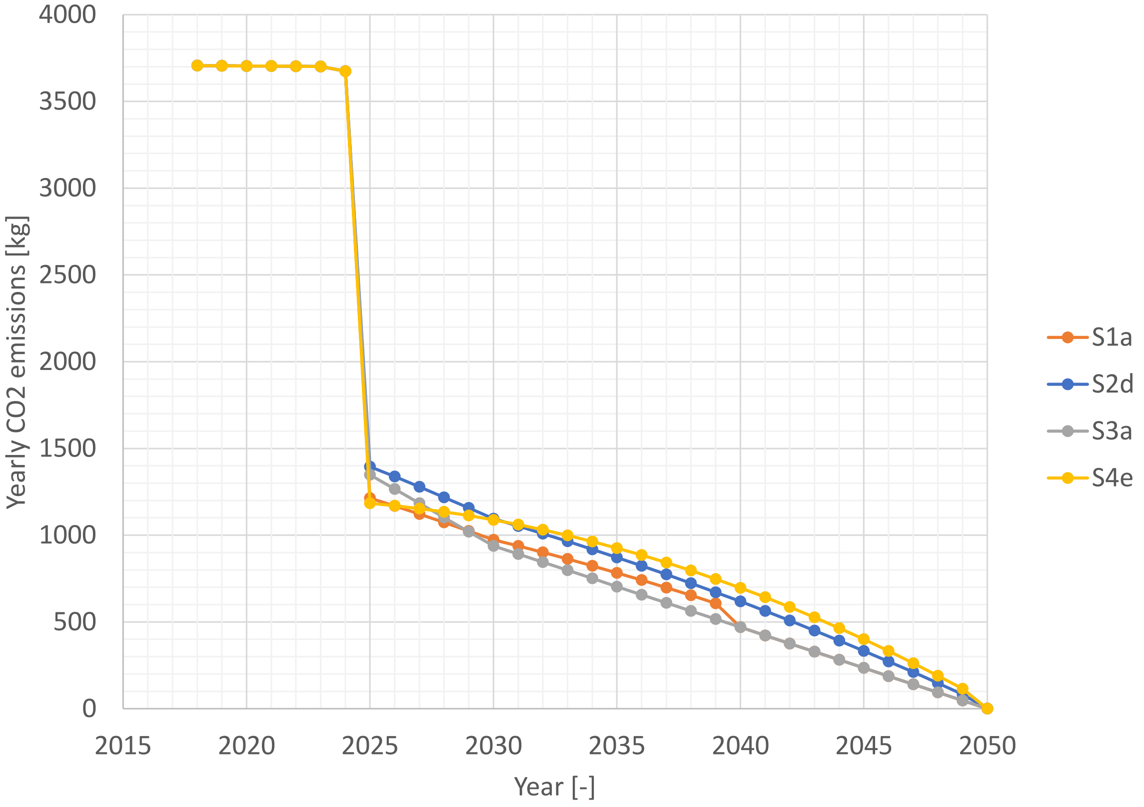

Figure 6.7: 'Preferred' design option (from the perspective of a home-owner) of each scenario compared in terms of CO_2 emissions

is applied, the chosen design option for the first three scenarios changes, while the fourth one, S4e, is the preferred design option from both perspectives. By applying the preference of the policy maker, the design options are chosen that apply high insulation at the first natural switching moment. This can be expected, as more insulation lowers the energy demand of the building and thereby also diminishes the CO_2 emissions related to that demand. Also, as has been stated earlier in this section, for all scenarios except the third, the high insulation design option also involves the lowest carbon reduction cost.

Table 6.7: 'Preferred' design option, from the perspective of a policy maker, of each scenario compared in terms of costs and environmental impact

		S1b	S2h	S3b	S4e
Total investment costs	[thousand €]	32	31	35	21
Total energy costs	[thousand €]	27	26	31	33
Discounted total costs	[thousand €]	45	44	47	40
Total yearly costs in 2025	[€]	1670	1670	2130	1380
Total yearly costs in 2040	[€]	2080	1790	2110	1730
Yearly costs summed	[thousand €]	59	56	65	54
Primary energy use	[GJ]	720	730	690	920
CO_2 emissions electricity	[tonnes]	5	4	12	0
CO_2 emissions gas	[tonnes]	32	33	26	45
Total CO_2 emissions	[tonnes]	37	37	38	45
Carbon reduction cost	[€/kg]	0.7	0.7	0.8	0.7

As can be seen in Table 6.7, these design options result in lower energy costs than the design option in Table 6.6, but also in significantly higher investment costs. Therefore, the costs (i.e., discounted and yearly costs) for the home-owner are higher. These design options do use significantly less primary energy, and emit significantly less CO_2, compared to the preferred design options by the home-owner.

6.6 Sensitivity analysis

In this section the sensitivity of key factors in the techno-economic analysis will be assessed. These key factors are the price of green gas, the share of green gas in the gas mix, the extra energy tax shift proposed in Klimaatberaad (2018) and the costs of insulation.

6.6.1 Green gas price

As has been stated before, the future development of the price of green gas is highly uncertain. Therefore, a sensitivity analysis will be performed that studies the influence of a higher and a lower green gas price development. The lower price development has been based on the expectation of Van Mellle et al. (2018) that the average production cost of green gas will be 0.49 €/m^3 in 2050. In this sensitivity analysis, a linear decrease from the current production price to the expected production price in 2050 is used as an assumption for a lower price development. For the higher price development the difference between the the original production price in 2050 and the lower production price of Van Mellle et al. (2018) is added to the original production price in 2050[2], after which a linear increase from the current production price is assumed. These new production price developments are shown in Figure 6.8, together with the original production price development and the corresponding developments of consumer prices[3].

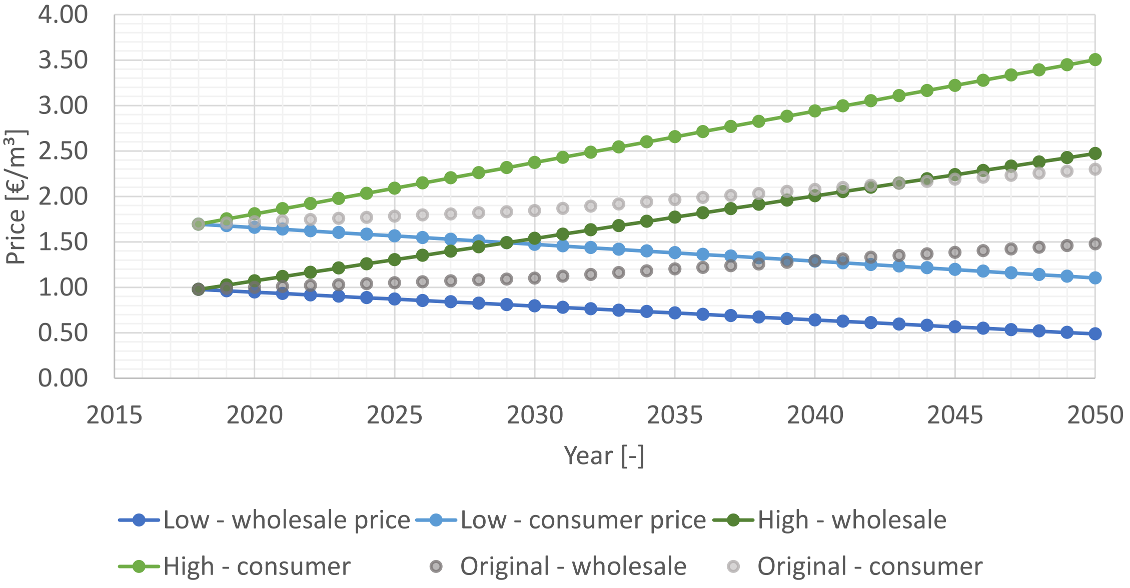

Figure 6.8: New high and low production price developments and their corresponding consumer price developments. The original price developments are shown as well.

Table 6.8 shows the results of applying the low and high green gas price developments on the techno-economic analysis. The table only shows the second and fourth scenarios, as these are most impacted by the change in green gas price (i.e., S1 and S3 stop using gas before the share of green gas in the gas mix becomes dominant, see Figure 3.9a). A complete overview of the sensitivity of the four scenarios can be found in Appendix F.2. The new price developments do not result in a change in the 'preferred' design option from the perspective of the home-owner (i.e., S2d and S4e are still the design options with the lowest yearly total costs in 2025 and 2040). The energy costs, discounted total costs and summed

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[2] Thus resulting in a production price of 2.46 €/m^3.

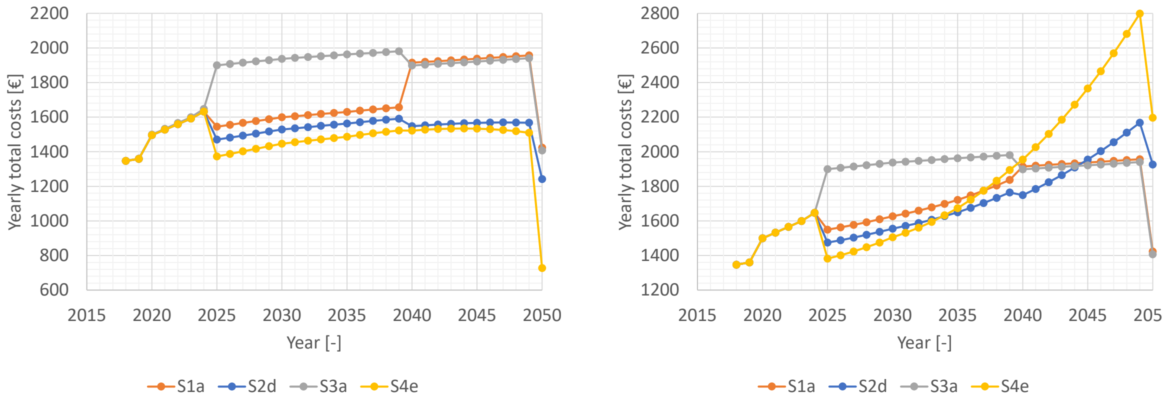
[3] The consumer prices are calculated in the way described in Section 3.5.2.

yearly costs increase with an increasing price development of green gas, thus also increasing the carbon reduction cost, but only slightly[4].

Table 6.8: Sensitivity of results after changing the price development of green gas

		S2d			S4e		
		Low	Original	High	Low	Original	High
Total energy costs	[thousand €]	36	38	41	28	33	39
Discounted total costs	[thousand €]	37	38	40	38	40	43
Yearly costs summed	[thousand €]	50	53	56	48	54	60
Carbon reduction cost	[€/kg]	0.6	0.7	0.7	0.6	0.7	0.8

Figure 6.9a shows that with a lower price development, the fourth scenario results in lower yearly costs over the complete studied period, with the second scenario only resulting in slightly higher yearly costs. The yearly costs of the fourth scenario even start to decrease around 2045 because green gas becomes less expensive than natural gas at that point. With a higher price development, Figure 6.9b shows that all scenarios that use gas up to 2040 (i.e., S1, S2 and S4) have significantly increasing yearly costs up to that year. However, the third scenario still has a higher yearly costs than the other scenarios up to 2040 as the share of green gas in the gas mix is low until that year (see Figure 3.9a).



(a) Lower green gas price development

(b) Higher green gas price development

Figure 6.9: Effect of a change in green gas production price development on the yearly total costs of the four scenarios

6.6.2 Step switch natural gas to green gas

As has been explained in Section 3.5.4, an assumption has been made regarding the gradual increase of green gas in the gas mix. A more simple approach is to apply a discrete step switch towards a renewable gas system on green gas, rather than a gradual increase. In the step switch, the gas 'mix' will change from 100 % natural gas to 100 % green gas in 2040.

Table 6.9 depicts the results of applying this step switch. The main difference with the original results is the change in preferred design option for the fourth scenario, which now switches to an all-electric system in 2040 because the yearly total costs of the all-electric system (S4g) is lower than the costs of the green gas system (S4e). With design option S4g, the building is highly insulated in 2025 and in 2040 the installation of the all-electric system is combined with the installation of low temperature radiators.

When comparing Table 6.9 with the original results in Table 6.6, it can be seen that the step switch results in only a slight decrease of costs for the first three scenarios and a slight increase for the fourth. Also in terms of primary energy consumption and CO_2 emissions, the step switch results in a slight change. Therefore, even though Figure 6.10 shows that the paths for the yearly costs and CO_2 emissions

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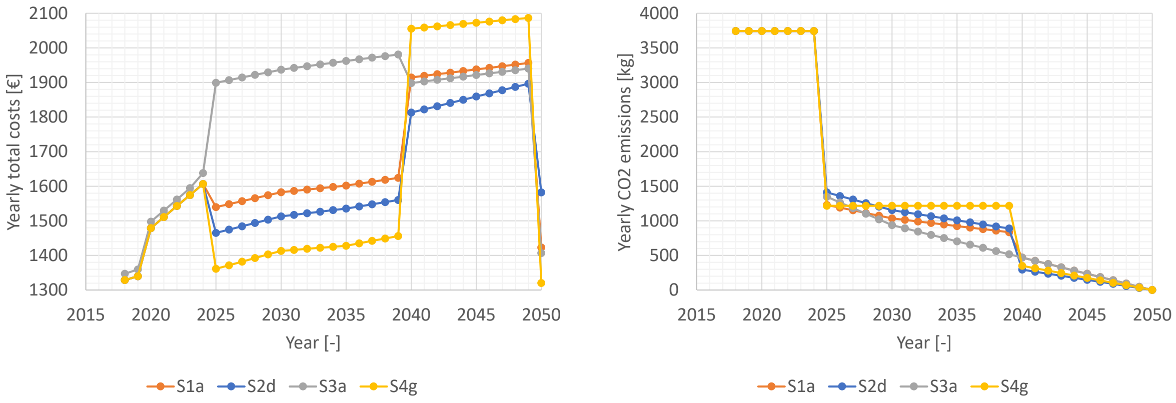
[4] In some cases the carbon reduction cost does not seem to change in Table 6.8, which is due to the rounding of the value.

Table 6.9: Results after applying a discrete step switch of the share of green gas in the gas mix

		S1a	S2d	S3a	S4g
Total investment costs	[thousand €]	22	16	23	21
Total energy costs	[thousand €]	34	39	38	28
Discounted total costs	[thousand €]	40	38	41	41
Yearly costs summed	[thousand €]	55	53	60	54
Primary energy use	[GJ]	840	850	760	930
CO_2 emissions electricity	[tonnes]	9	10	16	2
CO_2 emissions gas	[tonnes]	35	35	26	45
Total CO_2 emissions	[tonnes]	44	45	42	46
Carbon reduction cost	[€/kg]	0.7	0.7	0.7	0.7

when applying the step switch are different compared to the gradual increase of green gas, the results over the full studied period are similar.



(a) Effect on yearly total costs

(b) Effect on CO_2 emissions

Figure 6.10: Effects of applying a discrete step switch of the share of green gas in the gas mix

6.6.3 Extra tax shift in 2030

As has been explained in Section 3.5.2, an extra tax shift from electricity to natural gas has been proposed in Klimaatberaad (2018) (i.e., a decrease of 0.074 €/kWh and an increase of 0.2 €/m^3). Table 6.10 shows the results of applying this extra tax shift in 2030. The preferred design options (from the perspective of a home-owner) did not change for the scenarios. For the first three scenarios, the costs (i.e., energy costs, discounted costs and summed yearly costs) all decrease when applying this extra tax shifts, as they (partly) use electricity for heating (and DHW production). The fourth scenario only uses gas, resulting in an increase in costs.

Table 6.10: Sensitivity of results after applying an extra tax shift in 2030

		S1a		S2d		S3a		S4e	
		Old	New	Old	New	Old	New	Old	New
Total energy costs	[thousand €]	35	31	38	35	38	32	33	35
Discounted total costs	[thousand €]	40	39	38	37	41	38	40	41
Yearly costs summed	[thousand €]	56	52	53	50	60	54	54	55
Carbon reduction cost	[€/kg]	0.7	0.6	0.7	0.6	0.7	0.7	0.7	0.7

Figure 6.11 shows that as a result of the extra tax shift, the order of scenarios in terms of lowest yearly total costs changes in 2030. In that year, the fourth scenario becomes more expensive than the first and

second. In 2035, the fourth scenario also becomes more expensive than the third scenario. It can also be seen that the extra tax shift is not enough to make the all-electric scenario (i.e., S3) less expensive than the scenarios that use a hybrid heat pump (i.e., S1 and S2). So, even though the extra tax shift does not result in a large decrease of carbon reduction cost for the scenarios (see Table 6.10), it does have a significant effect on the yearly total costs.

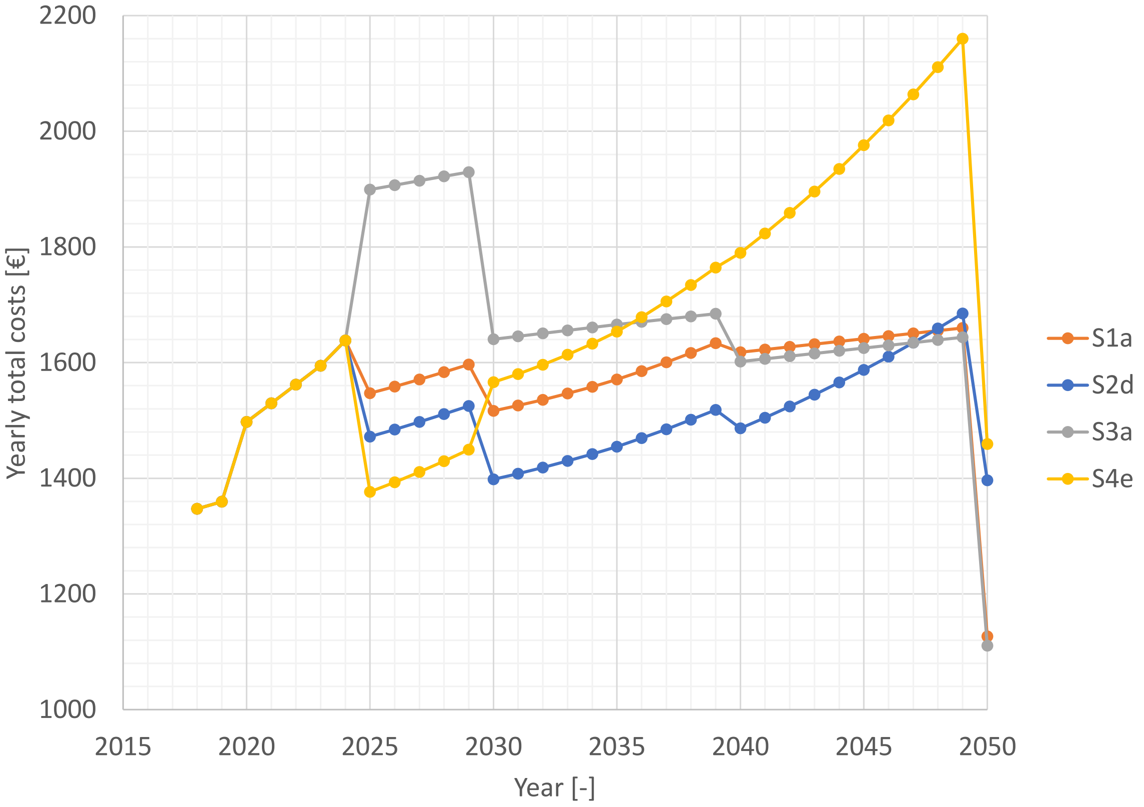


Figure 6.11: Yearly energy costs of the four scenarios when applying an extra tax shift in 2030

6.6.4 Higher insulation costs

It has also been studied what the effects are of an increase in insulation costs on the techno-economic results of the scenarios. An increase of 50 % has been applied on the insulation costs, of which the effects are shown in Table 6.11.

Table 6.11: Sensitivity of results after increasing the costs of insulation

		S1a		S2d		S3a		S4e	S4i	S4e
		Old	New	Old	New	Old	New	Old	New	New
Total yearly costs in 2025	[€]	1550	1710	1470	1630	1900	2060	1380	1560	1760
Total yearly costs in 2040	[€]	1910	2080	1640	1810	1900	2060	1730	2050	2110
Yearly costs summed	[thousand €]	56	60	53	57	60	64	54	60	64
Carbon reduction cost	[€/kg]	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.9	0.8

As expected, the costs increase for all scenarios. The most interesting effect of the higher insulation costs is the change of preferred design option for the fourth scenario, with the new preferred design option (S4i) switching to an all-electric system in 2040 instead of using a gas boiler (S4e). Design option S4i installs improved insulation in 2025 and combines the installation of an air-source heat pump with the installation of low temperature radiators in 2040. With this switch from S4e to S4i, all scenarios now switch to the improved insulation level in 2025. The S4i design option results in a higher carbon reduction cost than if the S4e design option was kept. Therefore, there is a discrepancy between the preferred design option for the policy maker (i.e., lowest carbon reduction costs) and the preferred design option for the home-owner (i.e., lowest yearly costs).

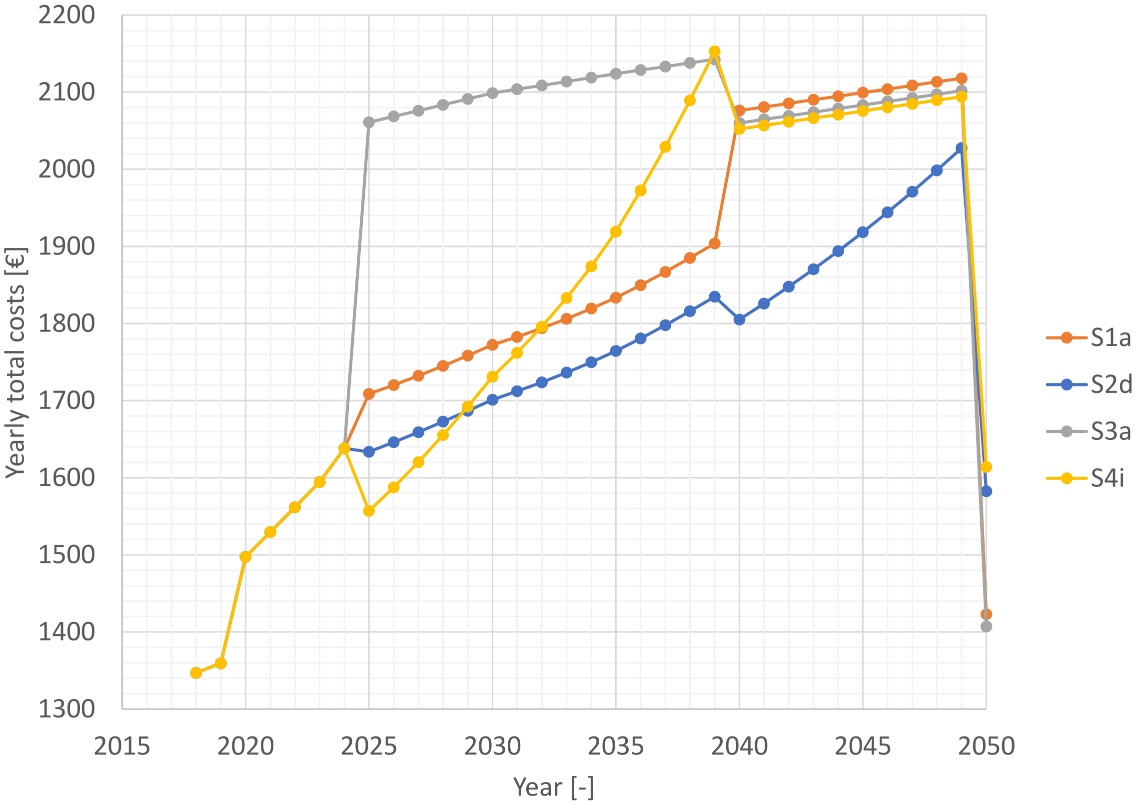


Figure 6.12: Yearly energy costs of the four scenarios when increasing the costs of insulation

Figure 6.12 shows that in 2025, the fourth scenario offers the lowest yearly costs, but quickly becomes more expensive then the hybrid heat pump scenarios in the following years. After 2040, S1, S3 and S4 have similar yearly costs, with S2 offering significantly lower costs, but which also increases steadily.

6.7 Concluding remarks on the techno-economic impact of the scenarios

It can be stated that for each scenario, a design option was found that is preferable over the business-as-usual case introduced in the beginning of this chapter (i.e., preferable at least in terms of costs). A general remark is that applying insulation will result in lower costs and less CO_2 emissions.

From the perspective of the home owner, Figure 6.6 shows that if the home owner only looks at the costs in the years of the natural switching moments, the fourth scenario will be preferred, as it results in the lowest yearly costs in 2025 and the second lowest yearly costs in 2040. However, Table 6.6 shows that if the yearly costs are summed over the whole studied period, it can be seen that the second scenario comes out cheaper due to the fast rising costs of the fourth scenario after 2040. However, Figure 6.6 also shows that in 2050, when the insulation measures have been written-off, the first and third scenarios have the lowest yearly costs. So, even though the first and third scenarios result in lower CO_2 emissions[5] and also result in lower yearly costs at the end of the period, these scenarios will less likely be chosen when the yearly costs during the transition period are prioritized.

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[5] Albeit only a difference of around 7 %, see Table 6.6.

Figure 6.11 shows that by applying an extra tax shift in 2030, the order of the scenarios in terms of yearly costs changes significantly, but the preferred design options do not change. If the home-owner takes this future tax shift into account when deciding in 2025, then the second scenario is preferable in terms of yearly costs, as the costs of the fourth scenario increase significantly after 2030. It can also be seen in Figure 6.11 that the extra tax shift results in the first three scenarios coming closer together in terms of yearly costs. The difference in yearly costs at the end of the transition period, when the insulation measures have been fully paid off in 2050, between the scenarios that end up with an all-electric system (S1 and S3), and the scenarios that end up with a system (partly) running on green gas (S2 and S4), is even larger with the extra tax shift. S1 and S3 both have significantly lower yearly costs in 2050. Table 6.10 shows that the extra tax shift has also resulted in the summed yearly costs of the scenarios being closer together.

There is a discrepancy between the preferred design options and scenarios of the home owner and the preferred design options and scenarios of the policy maker. In general, the policy maker would prefer the design options that insulate highly at the first natural switching moment. Also, while the home owner prefers the fourth scenario, the policy maker will likely prefer any of the other three scenarios, as they result in significantly lower CO_2 emissions.

Chapter 7

Combined results and implications

This chapter will combine the results from the scenario study, with the results from the simulation study and techno-economic analysis. It will reflect on some expectations regarding the hybrid heat pump and will address the implications of the results for the design of hybrid heat pumps, for home-owners and for policy makers.

7.1 Reflection on expectations regarding the hybrid heat pump

As has been described in Chapter 1, the hybrid heat pump is put forward as a promising technology to quickly start progressing in the transition towards a low-carbon heating system. This is specifically aimed at a decrease in natural gas use and CO_2 emissions with acceptable costs. Another proposed benefit is the good fit with the current heating system, thus providing a ‘quick-fix’ solution. This research performed a scenario study and a simulation study to assess the potential and role of hybrid heat pumps in the transition to a low-carbon heating supply for a typical existing Dutch house.

Table 7.1 shows the four studied scenarios, and specifies the trajectory type by Geels et al. (2016) that fits these scenarios, as well as the applied heating technologies in the scenarios, and the resulting CO_2 emissions and costs over the studied period (i.e., 2018-2050).

Table 7.1: Main results of both the scenario study and the simulation study

	Trajectory type	**Technology**	**Total CO_2 emissions** [tonnes]	**Yearly costs summed** [thousand €]
S1	Transformation trajectory, similarities with technological substitution	HHP to ASHP	42	56
S2	Transformation trajectory	HHP	45	53
S3	Technological substitution trajectory, similarities with transformation trajectory	ASHP	42	60
S4	Transformation trajectory with possibility to shift to technological substitution	Mono-gas to mono-gas or ASHP	45	54

Due to the similarities in system structure and actor network with the current regime, the two hybrid heat pump scenarios, S1 and S2, fit the transformation trajectory the most. However, as the HHP is replaced by an all-electric system in the second natural switching moment of the first scenario (i.e., in 2040), this scenario also has similarities with the technological substitution trajectory, as the use of gas in the heating system is completely replaced by electricity. The total CO_2 emissions and total costs of the two hybrid heat pump scenarios are similar, with the first scenario resulting in somewhat lower CO_2 emissions and somewhat higher costs.

The third scenario is most similar to the technological substitution trajectory as the gas-based heating system is radically changed to an electricity-based heating system. It does have similarities with the transformation trajectory, as incumbents will still have a role to play in this scenario. The total CO_2 emissions of this scenario are similar to the first HHP scenario, but the total costs are higher.

The fourth scenario starts off with a transformation trajectory when the mono-gas boiler system is kept in place while the share of green gas in the gas mix is slowly increased. In 2040, a decision has to be made to continue on this transformation trajectory towards a mono-gas boiler using 100 % green gas or to switch to an all-electric system, thus shifting to a technological substitution trajectory. In terms of yearly costs at the natural switching moments, the preference of the home-owner will be the first option, which is to stick with the mono-gas system. In that case the total CO_2 emissions of the fourth scenario are similar to the second (HHP) scenario, but with slightly higher total costs.

The potential of the hybrid heat pump can also be assessed by comparing it with the CO_2 reduction target for the built environment as set out by the Dutch national government in the climate agreement that is currently being made (Klimaatberaad, 2018). The target for the built environment is to reduce emissions by 3.4 million tonnes in 2030, compared to 1990. After correcting for the increase in the number of buildings, the required relative CO_2 reduction for each building is around 35 %[1]. Table 7.2 depicts the CO_2 emissions in 2030 of the four preferred design options for the home-owner. It can be seen that all four preferred design options result in a larger relative CO_2 reduction than 35 %. The reference level for this relative reduction is the amount of CO_2 emitted by the mono-gas boiler system with the current insulation level in 2018[2], which was around 3700 kg.

Table 7.2: Climate impact of the four preferred design options (by the home-owner) compared in 2030 and the relative reduction in 2030

		S1a	S2d	S3a	S4e
CO_2 emissions in 2030	[kg]	970	1540	940	1090
Relative reduction in 2030	[-]	-0.74	-0.58	-0.75	-0.71

However, by comparing the preferred design options, the effects of extra insulation measures and of a change of heat source are combined, therefore making it not possible to assess the climate impact of only the hybrid heat pump. Table 7.3 compares the hybrid heat pump to the mono-gas boiler for the two insulation levels that use high temperature radiators. It can be seen for both the current and improved-HT insulation level that the hybrid heat pump results in significantly lower CO_2 emissions than the mono-gas boiler system. However, for the current insulation level, the relative reduction in 2030 is not large enough to meet the 35 % reduction target. For the improved-HT insulation level, the relative reduction of the hybrid heat pump system is more than enough, but the reduction of the mono-gas system is also adequate.

Table 7.3: Climate impact of the hybrid heat pump system compared to the mono-gas boiler system in 2030 and within one lifetime, for the current and improved-HT insulation levels

	Insulation level:	Current		Improved-HT	
	Heat source:	HHP	Mono-gas	HHP	Mono-gas
CO_2 2030	[kg]	2760	3350	1090	2010
Relative reduction 2030	[-]	-0.26	-0.10	-0.71	-0.46
CO_2 one lifetime	[tonnes]	38.4	46.4	15.3	27.9

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[1] Data for the amount of houses in 1990 was taken from CBS (2018f). A prognosis for the amount of houses in 2030 was used from Ministerie van Binnenlandse Zaken en Koninkrijksrelaties (2016). Data for the amount of houses and building in general in 2017 was taken from CBS (2018e). The ratio between houses and buildings in general in 2017 was also used for 1990 and 2030. Data for the CO_2 emissions of the built environment in 1990 was used from Compendium voor de Leefomgeving (2009). A 3.4 Mton CO_2 reduction target for the built environment in 2030 results in an average decrease of 1.5 tonnes of CO_2 for each building, compared to 1990. The average relative reduction per building is 35 %.

[2] As the current insulation level mainly has double glazed windows, the CO_2 emissions related to this insulation level might be lower than the actual amount of emissions in 1990.

For the results displayed in Table 7.3 regarding the amount of CO_2 emitted within one lifetime, it should be noted that the results depend on when the heat sources are installed, as the CO_2-intensity of electricity and the gas mix changes over time. It can be concluded from Table 7.3 that switching to a hybrid heat pump does result in a significant decrease in CO_2 emissions compared to the mono-gas system, but also that without extra insulation, the decrease will not be adequate to reach the 35 % relative reduction target. However, as explained in Section 5.3.2, installing a hybrid heat pump does result in a significant decrease in gas use, which is on its own also one of the proposed benefits of the HHP system.

7.2 Implications for the design of HHPs

The bivalent-alternative operation mode was compared to the bivalent-parallel operation mode in terms of primary energy consumption in Section 5.2.2. It was found that for all insulation levels and for all considered heat pump capacities there was only a limited difference between the two operation modes. In the research by Bagarella et al. (2016a), it was found that the bivalent parallel operation mode resulted in a lower primary energy consumption for low capacity heat pumps in hybrid heat pump systems, while there was no significant difference for large heat pump capacities. In the current study, this pattern was only found in two of the four insulation levels, thus not providing a conclusive result. A significant difference between the two operation modes was found when the f-factors were considered, with the parallel operation resulting in lower f-factors. However, this might be a result of the limitation in the model that the heat pump supplies heat instantaneously, which will be addressed in Section 9.1.1.

In the all-electric ASHP models, a clear trend was visible of a decreasing heat pump capacity with increasing insulation levels. However, for the hybrid heat pump models, this trend was not visible. The high insulation case does result in a lower ‘preferred’ heat pump capacity than the improved insulation cases but the current insulation case has the lowest preferred heat pump capacity. This is probably because of the poor operation of the heat pump in the current insulation case, resulting in the gas boiler operating more efficiently in terms of primary energy, relative to the heat pump. Therefore, the preferred heat pump capacity of the current insulation case is low with a high bivalent temperature.

7.3 Implications for home-owners

In the first scenario, the regime first transforms gradually from a heating system based on natural gas to a mixed heating system using electricity as well as gas. The hybrid heat pump acts as a stepping stone for not only the home-owner, but also provides time for the municipality and the DSO to prepare for the switch to an all-electric system. In the second step, in 2040, gas is no longer used for heating and a next transformation occurs to an all-electric system. The design option with the lowest yearly costs is the one where improved insulation as well as low temperature radiators are installed in 2025, together with a hybrid heat pump. This will lead to a reduction of yearly costs in 2025. In 2040, the switch is made to an all-electric system. Even though no extra insulation is installed, the switch to an all-electric system does result in an increase in yearly costs in 2040. In 2050, when the insulation has been paid-off, the yearly costs are back at the around the same level as now (i.e., 2018) after having increased during the transition to a low-carbon heating supply.

The second scenario is similar to the first scenario in the first period, but in this case, the hybrid heat pump acts as an end-solution by using 100 % green gas in 2050. This transition has occurred more gradually then the first, as the heating system is still similar to the original natural gas based system. In this scenario, the design option with the lowest costs also installs improved insulation in 2025, but sticks with the high-temperature radiators. In 2040, no change is made, only that the share of green gas in the gas grid is quickly increasing to 100 % in 2050. These changes come with a decrease in yearly costs in 2025 as well as a slight decrease in 2040. However, in 2050, the yearly costs will be around 17 % higher compared to 2018.

In the third scenario, a much more radical change occurs when the gas-based heating system is substituted by an electricity-based heating system in 2025. The preferred design option insulates the building to the improved level in 2025 and also installs low temperature radiators. This change will involve a significant increase in costs in 2025 and a smaller decrease in costs in 2040. In 2050, the yearly costs are back at around the same level as the yearly costs in 2018.

In the fourth scenario no change occurs in the heating system in 2025, as the building is still heated by solely a gas boiler. However, in 2040, a choice has to be made to switch to an all-electric system or to stick with the gas boiler. Just as in the other scenarios, after 2040, the share of green gas in the gas grid is quickly increasing to 100 % in 2050. When determining what to do based on the yearly costs in 2025 and 2040, the design option is preferred where in 2025 the high insulation level is applied, while keeping the high-temperature radiators. In 2040, the choice is made to stick with the gas boiler, as a switch to an all-electric system will cause an increase in costs due to the installation of low temperature radiators. In 2025, the yearly costs decrease after which the yearly costs steadily increase up to 2050, following the increasing price of the gas mix. In 2050, the insulation has been paid-off and the yearly costs return to slightly above the level of 2018. If the choice had been made for the all-electric system, the costs in 2050 would have returned to slightly below the level of 2018.

If the four scenarios are compared while just looking at the yearly costs, it can be concluded that in 2025 the preferred scenario is the fourth scenario, which means no change in the heat source. However, this scenario will become significantly more expensive between 2040 and 2049. When looking at the yearly costs summed over the whole considered period, the second scenario is preferable. This scenario however, does end up with the highest yearly costs at the end of the period in 2050. The most expensive scenario is the third scenario, where the all-electric option results in the highest costs during the transition.

When comparing the design options of the fourth scenario and when comparing the scenarios with each other, it is important to note that only looking at the yearly costs at the natural switching moments (i.e., in 2025 and 2040) will provide limited insight in the costs over the whole transition period, mainly because the price of gas will increase quickly with an increasing share of green gas.

The implications mentioned above only take into account the costs of the heating and DHW system. Other factors that might affect the decision of the home-owner are for example the use of gas for cooking, the noise produced by air-source heat pumps and the hassle associated with installing extensive insulation measures.

7.4 Implications for policy makers

The preferred design options for the home-owner are not the preferred ones for the policy maker, for the four scenarios. The key issue here is that most of the scenarios described above install improved insulation while installing high insulation results in lower CO_2 emissions at around the same carbon reduction costs.

One option policy makers have is to apply an extra tax shift from electricity to gas in 2030. However, Section 6.6.3 has shown that although this tax shift does change the preferred order of the four scenarios for the home-owner, with the second scenario having a lower yearly costs development than the fourth, it does not result in a change in the preferred design option to options that apply high insulation in 2025. Still, a change from the fourth scenario to the second does results in a decrease in CO_2 emissions of 18 %. However, if the government wants to discourage the fourth scenario, which sticks with the mono-gas boiler for longer, an earlier introduction of this extra tax shift might be effective, as it does change the order of the four scenarios in terms of yearly total costs.

As has been explained in Section 4.2.1, a requirement for the building-bound financing scheme is that the monthly expenses of the loan are not higher than the energy savings resulting from the building improvements. Whether or not this goal is achieved in the scenarios can be assessed by looking at the change in yearly costs in 2025, when the building adaptations are applied. As the investments costs in the building adaptations are included in these yearly costs, over a write-off period of 25 years, a decrease in these costs indicates that the energy savings are greater than the extra costs due to the write-off of the building adaptations, while an increase in these costs indicates the opposite. Of the design options that applied building adaptations in 2025 in the first scenario, one out of three resulted in lower yearly costs. For the second scenario this was two out of three, for the third scenario this was none out of two and for the fourth this was two out of two[3]. This indicates that the building-bound financing scheme is effective in some scenarios, but not all. It is most effective in the fourth scenario, where the heat source is not

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[3] Only the design options were considered that applied building adaptations in 2025. Also, design options that applied the same building adaptations were not counted double in each scenario.

changed and it is least effective in the third scenario, when a switch is made to an all-electric system.

It is also interesting to reflect on the ‘neighbourhoods without natural gas’ (i.e., ‘aardgasvrije wijk’ in Dutch) program. An all-electric system with air-source heat pumps is one of the options in such programs. The first and third scenario both end up with an all-electric system, with the main difference that the first scenario uses the hybrid heat pump as a stepping stone. The results of the techno-economic analysis show that using the hybrid heat pump as a stepping stone significantly reduces the costs for the home-owner while resulting in a similar emission of CO_2. Therefore, it is also interesting to consider hybrid heat pumps in the context of ‘neighbourhoods without natural gas’, even though it does not result in an immediate shift to a neighbourhood without natural gas. The HHP offers one more benefit that is relevant for this program, which is the fact that it is a relief of some pressure for the DSO to reinforce the grid in anticipation of an all-electric neighbourhood.

Also the manifest to ban mono-gas systems can be reflected upon with the results from this study. In the article by De Ronde (2018), the Dutch federation of energy consultants, FedEC, argues that the regulation proposed in the manifest is not a good measure in the transition to a low-carbon heating supply. They argue that without good insulation measures, a ban on mono-gas boilers will result in higher costs while the decrease in gas use is only moderate. The results of this thesis show that, for the studied building, changing to a hybrid heat pump does result in a significant decrease in gas use for the improved and high insulation levels (i.e., a decrease of roughly 60 %). However, for the current insulation case, the decrease in gas use is less high (i.e., a decrease of roughly 30 %). In terms of costs, the results of this research show that keeping the mono-gas system results in the lowest yearly costs for the home-owner in 2025. That is however in combination with the high insulation level and will quickly increase in costs over the following period. So, both in terms of costs and in terms of the decrease in gas use, the results from this study agree with FedEC in that any change in the heat source will have to be combined with insulation measures in order for a ban on mono-gas system to have a positive effect on the transition to a low-carbon heating supply.

Chapter 8

Conclusion

The goal of this study was to answer the following two research questions:

1. *What is the potential of the hybrid heat pump in renovation projects of a typical Dutch house?*
2. *What could be possible roles of the hybrid heat pump in the transition towards a low-carbon heating system for this building?*

The study was performed on a typical Dutch terraced house, built between 1965 and 1974. The simulation showed that currently, in 2018, installing a hybrid heat pump will not result in benefits regarding CO_2 emissions or primary energy use. Installing an all-electric air-source heat pump will result in more CO_2 emissions. However, the hybrid heat pump does result in a significant decrease in gas use. In terms of energy costs, a HHP or an ASHP do not provide any benefits today. The current energy costs of a HHP are roughly equal to that of a gas boiler system while the energy costs of an ASHP are significantly higher.

Therefore, it can be concluded that, when only looking at the current benefits and costs, the hybrid heat pump, as well as the all-electric heat pump, have limited potential. To study the potential and role of the hybrid heat pump in the future, four socio-technical scenarios were made.

In the first scenario the HHP acts as a stepping stone to an all-electric system. This stepping stone role is fulfilled by providing preparation time for infrastructure adaptations, as they involve complex considerations, high investments and also requires a larger workforce. In the second scenario, the hybrid heat pump is the end-solution itself by using a gas mix that is fully renewable in 2050. The hybrid heat pump still has an enabling role in the second scenario as it decreases the gas demand of the building, as the scarcity of green gas is an important issue. In the third scenario, a radical change occurs and the hybrid heat pump has no role in the transition, as the step is taken to switch to an all-electric system straight away. In the fourth scenario, the decision to change the heat source is postponed, as the gas boiler is kept as a heat source in 2040. In 2040 a decision has to be made on how to change to a renewable heating supply. Two options emerge, to switch over to an all-electric system or to keep the gas boiler which will run completely on green gas in 2050. Thus, the hybrid heat pump has a role in the first two scenarios, and no role in the second two scenarios.

By performing a techno-economic assessment of the scenarios it was found that from the perspective of a home-owner, the fourth scenario is most viable, as this results in the lowest path of yearly costs. However, it should also be noted that all scenarios are viable in terms of the techno-economic results and all provide significantly improved results in comparison with the business-as-usual case. The carbon reduction costs of all four scenarios is similar. It was also found that in three of the four scenarios, the improved insulation level is applied if the yearly costs is the leading criteria in deciding on what design option to apply. By applying the high insulation level, less CO_2 will be emitted due to the lower heat demand.

With regards to the short-term potential of the hybrid heat pump, it was found that the hybrid heat pump results in significantly lower gas use, as well as lower CO_2 emissions. However, insulation is key and has a large impact on the costs and CO_2 emissions, more than a change in heat source. Without applying insulation, the hybrid heat pump will not be able to provide an adequate reduction in CO_2 emissions in 2030, in order to match the average reduction target of 35 % set in the climate agreement that is currently being made (see Section 7.1 for more details).

To summarize, there is potential in the hybrid heat pump in the transition towards a low-carbon heating supply. Even though it does not provide benefits when applying it now, future developments can provide a window of opportunity for hybrid heat pumps. However, this window of opportunity is also present for two competitors of the hybrid heat pump, which are the all-electric system with an air-source heat pump and green gas. Either way, the studied scenarios showed that there is a possibility to significantly reduce the greenhouse gas emissions during the transition while keeping the costs for the home-owner at a reasonable level. It is also clear that, if the scenario and/or design option has to be chosen by the home-owner that also results in the lowest CO_2 emissions, policy intervention will be necessary, as there is currently a discrepancy between the preferred options by the home-owner and the preferred options by the policy maker.

Chapter 9

Discussion

This chapter will address the limitations and assumptions in this research. It will also propose some future work that can arise from this study and its results.

9.1 Limitations and assumptions

The limitations of this research are split up into two segments; limitations in the simulations and the limitations of the assumptions. These will be dealt with separately. However, there are also some limitations that do fit these segments, which will therefore be described first.

The first limitations can be found in the scope of this research, which only focuses on individual heat sources, while collective solutions such as large or small heat grids can also be an option. The number of competing technologies for the hybrid heat pump has been limited to a gas boiler (running on natural and/or green gas) and an all-electric ASHP system. Other technologies that might be viable to study are micro CHPs (i.e., combined heat and power), solar thermal collectors, infra-red panels, green hydrogen and seasonal heat storage. Furthermore, the scope of the set of scenarios was limited to four different paths of heat source applications until 2050. When looking at Figure 6.6, it can be seen that a combination of S4 and S2 might have resulted in a more preferred scenario. In this combination the path of S4 is followed up until 2040 (i.e., keeping the gas boiler) after which in 2040 a switch is made to a hybrid heat pump system. This path has not been considered in this study.

It is important to note the significance of the timing of the natural switching moments and the end of the scenarios and calculations (i.e., 2025, 2040 and 2050 respectively). This influences especially the economic impact of insulation measures. Applying insulation immediately results in a lower heat demand, but also takes 25 years to be written-off. After these 25 years, is is still providing the benefit of a lower heat demand but because the costs have been paid off, the yearly total costs will be much lower. This can be seen in Figure 6.6, where the yearly costs in 2049 are very different from the yearly costs in 2050, when the insulation installed in 2025 has been fully paid-off.

Another limitation is the fact that societal costs have not been taken into account. A societal cost that is directly related to the choice of heat source is the infrastructure costs. For example, the costs related to reinforcing the electricity grid have not been taken into account. An indirect societal cost is the one related to the emission of greenhouse gasses. With a lower reduction of CO_2 emissions in the built environment, a larger reduction will be necessary in other sectors to reach the goals set in international agreements. More indirectly, higher CO_2 emissions can also result in more societal costs as the result of the impacts of climate change.

9.1.1 Limitations in simulations

Some limitations are present in the set-up of the simulation model, which will be described first, while others are present in the model itself. As has been explained in Section 5.3.2, the maximum f-factor criteria (i.e., $f_{HHP} < (1 + \alpha) \cdot f_{mono\text{-}gas}$) resulted in some models heating the building more adequately than others. Although these differences were relatively small, it did result in a trend break regarding an increasing load factor with increasing insulation. Instead of setting a maximum criteria for the f-factor, it might be better to make sure the f-factor is equal to the reference case of the gas boiler only model (i.e., $f_{HHP} = f_{mono\text{-}gas}$). Also, the use of the f-factor as a measure of thermal comfort can be debated. Although Orme (2015) does suggest that a 'temperature out-of-range' measure is a viable standard for measuring thermal comfort, it is also argued that it does not fully characterise thermal comfort as it is limited to quantifying temperature extremes. Using a heat balance standard (e.g., EN ISO 7730) might provide a more realistic measure of thermal comfort, as also stated by Orme (2015). Using a more refined thermal comfort standard might result in a different preferred system size for the HHP and ASHP models.

Another important limitation is the limited validation of the building model. It was only possible to compare the whole-year results of the gas use with the measures stated in the example building document by Agentschap NL (2011). Comparing to or directly using actual heat demand data might provide more realistic heat demand data, although it is still very dependent on the building construction and behaviour of the residents in either case. As the goal of this study was not to optimize the heating technologies but to make a comparative analysis, the constraint caused by lack of real data is limited.

Next, the limitations present in the model itself will be addressed. The thermostatic temperature control on the ground floor had a setpoint temperature of 22 °C when occupied and 18 °C when not occupied. These temperature setpoints were equal for all studied heating technologies, which can provide a limitation as the heat pump systems benefit from a more stable temperature setting. Also the heat pump component itself provided some limitations. As explained in Appendix B.7.2, the heat pump component is not able to modulate its compressor frequency and therefore the heat supply, and instead works in an on/off mode. Because of this, it is less able to correctly supply the heat demand and is not able to heat until a certain setpoint temperature of the space heating fluid. A modulating heat pump is also able to reduce cycling losses, which provides a significant benefit compared to on/off operation modes (Bagarella et al., 2016b). However, these cycling losses were not taken into account in the simulation, as the heat pump component instantly provides the heat to the system, which is another important limitation of this component, as has been described in Section 5.2.2.

As has been stated in Section 5.3.3, the control system of the DHW storage tank is not smart enough to take the improved operating conditions of the heat pump in summer into account when deciding on what heat source to use for heating the DHW, which is a limitation of its control system. The radiator component used by TRNSYS also provides a limitation, as it is modeled as solely a heat exchanging device which requires a circulating flow of water. In reality, the radiators can also supply heat if there is hot water inside without circulation, which also provides inertia in the system (see Appendix B.8 for more details).

Also the user profiles and temperature setpoints can affect the outcome of the simulations. Households that are more often at home will probably result in a higher space heating demand and vice versa and changing the temperature setpoints will result in a changed heat demand. Another factor that can result in a change in heat demand is the weather data used in the simulation. Furthermore, a changing climate has also not been taken into account in this study, as the same weather was assumed for each year of the techno-economic assessment.

9.1.2 Limitations in assumptions

As this study focuses on the future impacts of a transition to a low-carbon heating supply, it also involves important limitations regarding the assumptions made about future developments as these are inherently uncertain. Important assumptions have been explained in Section 3.5, of which the main ones were the price developments of green gas, natural gas and electricity, the development of the primary energy factor and CO_2-intensity of electricity and the future supply of green gas. The sensitivity of the price developments has been addressed in Section 6.6, where it was found that a change in energy taxing of natural gas and electricity, or a change in the production costs of green gas can significantly influence the outcome of the techno-economic assessment.

An important assumption that will be highlighted separately is that of the ratio of green gas in the gas mix. As the four scenarios all reach the target to have a completely renewable energy supply in 2050, the CO_2-intensity decreases to 0 in 2050 but also the ratio of green gas in the gas mix increases to 100 % in 2050. The probability of the assumption that there is adaquate renewable electricity available in 2050 can of course be debated but the availability of an adequate supply of green gas involves greater uncertainties. As has been explained in Section 4.2.3, there is a limited supply of biomass available in the Netherlands to produce green gas. Furthermore, other sectors than the built environment are also expected to be requiring a supply of green gas (e.g., industry, transport and the production of electricity). There might also be other types of existing buildings that could be requiring a priority over the studied building in terms of the supply of green gas, for example buildings with a monument status that are limited in their options regarding insulation measures. Therefore, the assumption that there will be 100 % green gas available to the studied building in 2050 can be considered highly uncertain. If there is a larger demand for green gas than supply, this will likely result in a higher price for green gas, which will affect mainly the fourth scenario.

9.2 Future work

As has been described above, future work can look into more scenarios for changing the heat source (e.g., a combination of the fourth and second scenarios). Also, including societal costs will enrich the analysis, especially with regards to infrastructure costs. As this study only focuses on one building type, there is also room for future work in including more building types. Another addition for future work is to include active cooling in the model. Especially with regards to the effects of the changing climate (i.e., warmer summers and milder winters, as expected by KNMI (n.d.)) in combination with the increasing insulation levels.

The simulations can be improved especially with regards to the heat pump and radiator components, as well as the temperature control system. Furthermore, the sizing strategy for the (hybrid) heat pumps can be improved with regards to the thermal comfort criteria that has been used. These limitations have been explained in Section 9.1.1.

For the control of the hybrid heat pump specifically, future work can also look into a parallel set-up of the heat pump and the gas boiler. The current operation system of the hybrid heat pump switches between the two heat sources driven by the outside temperature. Future work can also look into a system that is driven by the return temperature of the space heating fluid. Carter and Lancaster (2017) report that an operation system driven by the return temperature has the possibility to improve the performance of the HHP. Another option is to base the switching strategy between the two heat sources on dynamic prices. If the flexibility services that could be provided by the hybrid heat pump are given an economic value in terms of dynamic pricing, the hybrid heat pump could possibly be used to provide flexibility on the electricity grid.

In the current study, the combination of solar photovoltaic panels and a hybrid heat pump has not been studied. This was done because the current net metering scheme results in no economic benefits for the home-owner if the hybrid heat pump is controlled to match its production by the heat pump with the output of the solar panels (i.e., because the home-owner receives the full consumer price of electricity when supplying electricity back to the grid (Kamp, 2017)). However, it can also be expected that the current net metering scheme will be changed in the future (Duijnmayer, 2018), thus providing an interesting research topic to match the control system of the hybrid heat pump with the output of the solar panels.

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Appendix A

Building construction

A.1 Studied building and heating options in simulation

Table A.1: Studied building and heating options in the simulations. The studied heat sources are indicated in the rows and the insulation level and temperature level of the heat emitters (HT/LT) are indicated in the columns.

	Current - HT	Current - LT	Improved - HT	Improved - LT	High - HT	High - LT
Gas boiler	X		X		X	
Hybrid heat pump	X		X	X		X
Air-source heat pump	X		X	X		X

A.2 Converting infiltration rates from qv;10 to ACH

As TRNSYS uses ACH values for its infiltration rate input and the literature displayed these values in qv;10 format, these values had to be converted. This was done in the following way.

First the qv;10 value was converted to the v;10 value by multiplying it with the usable floor area A.

$$qv;10 \cdot A = v;10$$

The v;10 value is measured with a pressure difference of 10 Pa, to convert it to an ACH;50 value, it first needs to be converted to a v;50 value, with a pressure difference of 50 Pa. According to Landstra and Lenting (2012) the following equation is generally accepted to convert these values.

$$v_1 = v_2 / \frac{P_2^{\frac{2}{3}}}{P_1^{\frac{2}{3}}}$$

The ACH;50 can then be calculated by dividing the volume V by the v;50 value.

$$ACH;50 = \frac{v;50}{V}$$

According to Trechsel (1986) a rule of thumb to convert ACH;50 to ACH values is:

$$ACH = \frac{ACH;50}{20}$$

Thus resulting in the ACH value that can be inserted in TRNSYS.

A.3 Floor plans

Figure A.1: Floor plans of the studied example building

A.4 Internal heat gains

The internal heat gain values can be found in Table A.2. The values for the internal heat gains for lighting and equipment were derived from Hoes et al. (2011) and Plas (2017). The radiative/convective fraction was taken from Solar Energy Laboratory (2017). For the heat gains from people, the 130 W person from ASHRAE (2013) was used. This corresponds to one person with ‘degree of activity V’ (i.e., standing, light work, walking, in a 24 °C room). The building is occupied by three persons (Agentschap NL, 2011).

Table A.2: Internal heat gains

	Lighting	Electrical equipment	Person
Internal heat gain	0.48 W/m^2	1.92 W/m^2	130 W
Radiative fraction	80 %	50 %	58 %
Convective fraction	20 %	50 %	42 %

A.5 Ventilative cooling strategy

The ventilative cooling strategy has been based on Hamdy et al. (2017). when ventilative cooling is applied (i.e., the windows are opened), the ventilation increases by 5 and 8 ACH for the sleeping and living areas respectively. These are the maximum values from Hamdy et al. (2017). Ventilative cooling is applied when the following criteria have been met:

$$T_{living} > 25\,^{\circ}\mathrm{C}$$

$$T_{sleeping} > 23\,^{\circ}\mathrm{C}$$

$$T_{ambient} < T_{room}$$

Appendix B

Description of TRNSYS models

B.1 General set-up

The TRNSYS model simulates the building and the space heating and DHW system over a full year, with time steps of five minutes. Figure B.1 shows the general set-up of the TRNSYS models. Each block will be dealt with in more detail in the next sections.

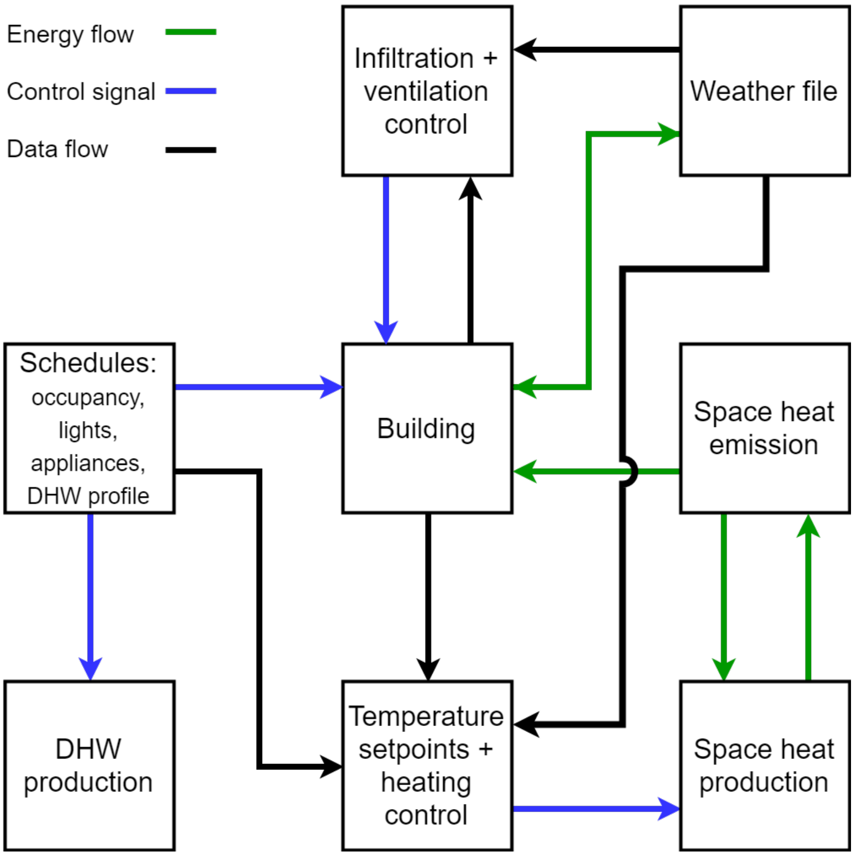

Figure B.1: General set-up of TRNSYS model, structured into eight main blocks, with energy flows, control signals or data flows between them

B.2 Building component

The building is simulated with the TRNSYS Type 56 Multi-zone building component. The building consists of three zones, one for each floor. The ground and first floors are heated, the attic is not. This component includes the zone geometries, the construction characteristics, zone characteristics (e.g., room temperature, internal capacitance) and heat gains (e.g., from occupants, lighting, appliances).

The building component interacts with many other components. Figure B.1 shows that the heat gains are controlled by the schedules components, the infiltration and ventilation rates are also controlled by other components. The building exchanges heat with the surroundings, represented by the weather file, and receives heat from the space heating system. Data on the room temperatures is used by the heating control components to control the space heating system.

B.3 Occupancy, lighting, appliances and DHW schedules

The schedules are made with the Type 14h general forcing function component for weekdays and for weekends. These are then combined into weekly schedules with the Type 41c forcing function sequencer component.

The occupancy schedule has been explained in Section 3.3.1. The lighting and appliance schedules follow the occupancy schedule (i.e., lighting and appliances are on if the zone is occupied). Section 3.3.1 also explains the schedule used for the DHW consumption.

As can be seen in Figure B.1, the schedule components control the heat gains in the building, as well as the DHW production. The schedule components also provide occupancy data to the temperature setpoints and heating control components.

B.4 Infiltration and ventilation control

The infiltration rate is constant over time, as explained in Section 3.3.1. Ventilation is split up into a constant ventilation rate and a ventilative cooling rate. Section 3.3.1 describes the constant ventilation rate while the ventilative cooling strategy is explained in Appendix A.5. The constant infiltration and ventilation rates are controlled by an Equation block while the ventilative cooling rate is controlled by two Type 2b differential controller with hysteresis components, one for each heated zone. As can be seen in Figure B.1, these components control the ventilation rate in the building component, while the building also supplies data on the room temperatures. The weather file supplies outside temperature data.

B.5 Weather file

The weather data used in the calculations is an IWEC (International Weather for Energy Calculations) dataset for Amsterdam by ASHRAE (2001). It is read by a Type 15-3 weather data reading and processing component. This component supplies the weather data to the ventilation control and the heating control components in the model. The building component exchanges heat with its surroundings by using the weather data.

B.6 Temperature setpoints and space heating control

The space heating is controlled with a setpoint temperature for the ground floor room temperature. This setpoint temperature is governed by the fact if the ground floor is occupied or not, has been described in Section 3.3.1 and is processed by an Equation block.

The control signal for the gas boiler is processed by a Type 23 PID controller component. This component iteratively tries to find the required heating capacity by the gas boiler to match the ground floor temperature with the setpoint temperature. The output of this component is a continuous value between 0 and 1, with 0 being the gas boiler should be off and 1 meaning the gas boiler should operate at full capacity. An equation block is used to prioritize the production of DHW over space heating (i.e., the gas boiler is not producing heat for the space heating system while it is producing heat for the DHW).

The control signal for the heat pump is processed by a Type 2b differential controller with hysteresis component as follows:

If the heat pump was previously ON:

$$T_{room} \geq T_{setpoint} + \frac{\delta T}{2} \rightarrow \text{switch OFF}$$

$$T_{room} < T_{setpoint} + \frac{\delta T}{2} \rightarrow \text{remain ON}$$

If the heat pump was previously OFF:

$$T_{room} \geq T_{setpoint} - \frac{\delta T}{2} \rightarrow \text{remain OFF}$$

$$T_{room} < T_{setpoint} - \frac{\delta T}{2} \rightarrow \text{switch ON}$$

With δT as the bandwidth within hysteresis occurs (i.e., where the state of the signal is equal to the state in the previous time step). For the case of the heat pump, this bandwidth is set to 1 °C. This governing set of rules results in the heat pump switching on and off to oscillate the temperature within this bandwidth around the setpoint temperature.

When the hybrid heat pump is used, another control mechanism has to be added that decides which heat source is on and which is off. This has been done with an Equation block that uses the outside dry bulb temperature and the cut-off and bivalent temperatures, as has been explained in Section 3.3.2.

B.7 Space heat production

Space heating is produced by a gas boiler and/or an air-water heat pump. The space heating water is circulated by a Type 3b single speed pump component at 400 kg/hr.

B.7.1 Gas boiler

For the gas boiler the Type 700 simple boiler with efficiency inputs component is used. As has been described in Section 3.3.2, the gas boiler has an efficiency of 96%, which is assumed to be constant in this component. Table B.1 also shows the setpoint temperatures for the three considered insulation levels. These were found by trial-and-error when minimizing the primary energy use of the mono gas boiler model. The continuous control signal (between 0-1) from the PID controller governs the capacity used to reach the setpoint temperature of the gas boiler.

Table B.1: Inputs for the Type 700 TRNSYS gas boiler component

Insulation level		Current	Improved	High
Boiler capacity	[kW]	19.5	19.5	19.5
Boiler efficiency - space heating	[%]	96	96	96
Boiler efficiency - DHW production	[%]	82	82	82
Setpoint temperature - space heating	[°C]	80	60	45
Setpoint temperature - DHW production	[°C]	60	60	60

B.7.2 Air-water heat pump

For the air-water heat pump the Type 941 air-to-water heat pump with neglected humidity effects component is used. The humidity effects can be neglected as the exhaust air of the air heat exchanger is the ambient air. This component uses an external datafile to model a heat pump. This datafile should be normalized to the rated condition of the heat pump to which the datafile belongs. This normalized data can then be used to scale the component to model different heat pump capacities without using a separate datafile for each capacity.

The datafile that was used in this study is from the Mitsubishi Electric Ecodan SUHZ-SW45VA split unit heat pump (Mitsubishi Electric, 2017). The rated conditions of this heat pump can be found in Table B.2. The datafile was then normalized to the rated conditions to be used in the TRNSYS component. The defrosting operation is taken into account in the used data file.

Table B.2: Rated conditions for the Mitsubishi Electric air-water heat pump from which the datafile was used (Mitsubishi Electric, 2015)

Rated heating capacity (A2/W35)	[kW]	3.25
Rated power	[kW]	0.94
Blower power	[kW]	0.06
Total air flow rate	[m^3/s]	0.743

An important limitation of this TRNSYS component is that it cannot modulate the compressor frequency. Most modern air-water heat pump are able to modulate the compressor frequency to more accurately meet the heat demand compared to an on/off system (Bagarella et al., 2016b). As the TRNSYS component is only able to process the data of one compressor frequency, it was chosen to use the data for the maximum compressor frequency of the heat pump from Mitsubishi Electric. The maximum compressor frequency was chosen due to a second limitation of the TRNSYS component which is related to the first limitation: the component is not able to operate towards a certain setpoint temperature for the heated water. Therefore it was chosen to operate the heat pump at maximum compressor frequency so to reach the highest possible water temperature at the given conditions.

B.8 Space heat emission

As has been explained in Section 3.3.1, the central heating system of the building uses radiators to exchange the heat from the hot space heating water to the rooms. Each heated zone of the building is heated by one Type 1231 hydronic heat-distributing unit component. This component calculates the heat exchanged between the space heating water and the air in the room, through a hydronic heat-distributing unit (e.g., a radiator or convector).

Table B.3: Rated conditions for the radiators used in the TRNSYS models

		HT radiator		LT radiator	
		Ground floor	First floor	Ground floor	First floor
Design capacity	[kW]	10.4	8.9	10.4	8.9
Design supply temperature	[°C]	75	75	55	55
Design room temperature	[°C]	20	20	20	20
Design delta-T exponent	[-]	1.3	1.3	1.5	1.5
Number of pipes	[-]	104	89	104	89
Pipe inside diameter	[m]	0.046	0.046	0.032	0.032

Table B.3 shows the rated conditions for the two types of radiators used in the models. The required capacity for the radiators was calculated in Section 3.3.1 where it was showed that the radiator capacity should be 10.4 and 9.9 kW respectively on the ground floor and first floor. This is when the supply temperature and room temperature are at the rated conditions: 75 °C and 20 °C respectively.

The high temperature (HT) radiators used in the model are designed for these temperatures. TRNSYS uses a value called the delta-T exponent to distinguish the heat transferring capability of different types of heat emitters. The HT radiators are assumed to be the original radiators that were placed when the building was built (between 1965-1974), which are cast-iron radiators. This corresponds to a delta-T exponent of 1.3. The number of pipes has been based on Deng et al. (2016), who use 10 pipes per kW of heating capacity. The pipe inside diameter of the HT radiators has been based on the DRL Multicolom radiator (DRL Products, 2015).

The low temperature (LT) radiators used in this study are so-called Low-H_2O radiators (Jaga, 2016; Milieu Centraal, n.d.-f), which actually use a convector to emit the heat at low temperatures. Therefore, the delta-T exponent is 1.5, which corresponds to a convector heat emitter. The LT radiators used in this study are designed to operate at 55 °C. The number of pipes and the pipe inside diameter have been based on Deng et al. (2016).

The Type 1231 component has two important limitations. The first is that it is modelled as solely a heat exchanging device. Therefore, it only emits heat if the space heating water is flowing. In reality, the radiators can continue transferring heat to the environment while there is hot water inside, even if the water is no longer circulating[1]. This issue was avoided by having the circulation pump always pumping the space heating water through the system, even if the heat sources are switched off. As has been explained in Section 3.3.1, the power consumed by the circulation pump is not taken into account.

The second important limitations is the fact that the TRNSYS component is only able to cope with an energy flow from the radiator to the room air. On warmer days, this results in an issue when the room temperature can rise higher than the space heating water. Consequently, the simulation produces an error and stops. This issue was circumvented by skipping the radiator component if the supply temperature of the space heating water was lower than 25 °C, when the heat transfer to the room air would have been low in any case.

B.9 DHW production

In the mono gas boiler and the hybrid heat pump systems, the gas boiler is producing the DHW. Table B.1 shows the efficiency (see Section 3.3.2 for more information) and the setpoint temperature (see Section 3.3.1 for more information) for the DHW production by the gas boiler. For the DHW production, the same Type 700 component is used as for the space heating production. As has been explained before, the DHW production has priority over the space heating produced by the gas boiler.

As has been explained in Section 3.3.2, the DHW in the all-electric system is produced by a DHW storage tank that is heated by the heat pump through a heat exchanger coil and by an auxiliary electric heater. This set-up has been based on the Techneco Loria Duo heat pump system (Techneco, 2018).

Table B.4 shows the properties of the DHW storage tank in the all-electric system. As the Techneco Loria Duo documentation did not specify the loss coefficients, the top, bottom and edge loss coefficients were based on a 150 litres storage tank by OEG (HGB Trading, n.d.), which was insulated with 50 mm of rigid PU foam. The flue loss coefficients are unknown and therefore kept at the default TRNSYS value. The tank has been divided into six isothermal layers, with node 1 at the top and node 6 at the bottom. Cold water enters at the bottom and hot water exits at the top. The total mass of water in the tank is kept constant. The Type 534 vertical cylindrical storage tank with immersed heat exchanger component is used for the DHW tank and the heat exchanger. The Type 1226 tank heating device component is used for the auxiliary heater.

The heat pump heats up the DHW in the tank via a coiled tube heat exchanger, which is located in the bottom half of the tank. If the heat pump is producing heat for the DHW tank, it is not producing heat for space heating. However, due to flow convergence issues, the fluid exiting the heat exchanger in the tank has to be circulated through the space heating system. Therefore, the heat pump is still providing some space heating in DHW operation. An auxiliary electric heater is located in the fourth node of the

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[1] This is especially the case with the HT radiators, which have a higher volume than LT radiators.

Table B.4: Properties of the DHW storage tank

Tank properties		
Volume	[L]	181
Tank height	[m]	1.49
Top/bottom/edge loss coefficient	[W/m^2·K]	0.46
Flue loss coefficient	[W/m^2·K]	0.83
Number of tank nodes	[-]	6
Entry node DHW	[-]	6
Exit node DHW	[-]	1
Heat exchanger coiled tube		
Inner tube diameter	[m]	0.20
Outer tube diameter	[m]	0.22
Heat exchanger wall conductivity	[W/m·K]	0.59
Length of coiled tube	[m]	15.7
Tank nodes for coiled tube	[-]	4-6
Auxiliary heater		
Tank node for electric heater	[-]	4
Heating capacity	[kW]	1.6

tank.

The storage tank is kept at the required temperature in the following way. The heat pump heats up the water in the storage tank up to 48 °C. Then, the electric heater takes over to heat up the water up to 55 °C. There is a hysteresis bandwidth of 1 °C when the electric heater takes over from the heat pump. This control system uses the Type 2b differential controller with hysteresis component together with an Equation block and a Type 113 basic aquastat component to measure the water temperature in the tank at the fourth node.

B.10 Schematics of space heating and DHW system for the three studied heat sources

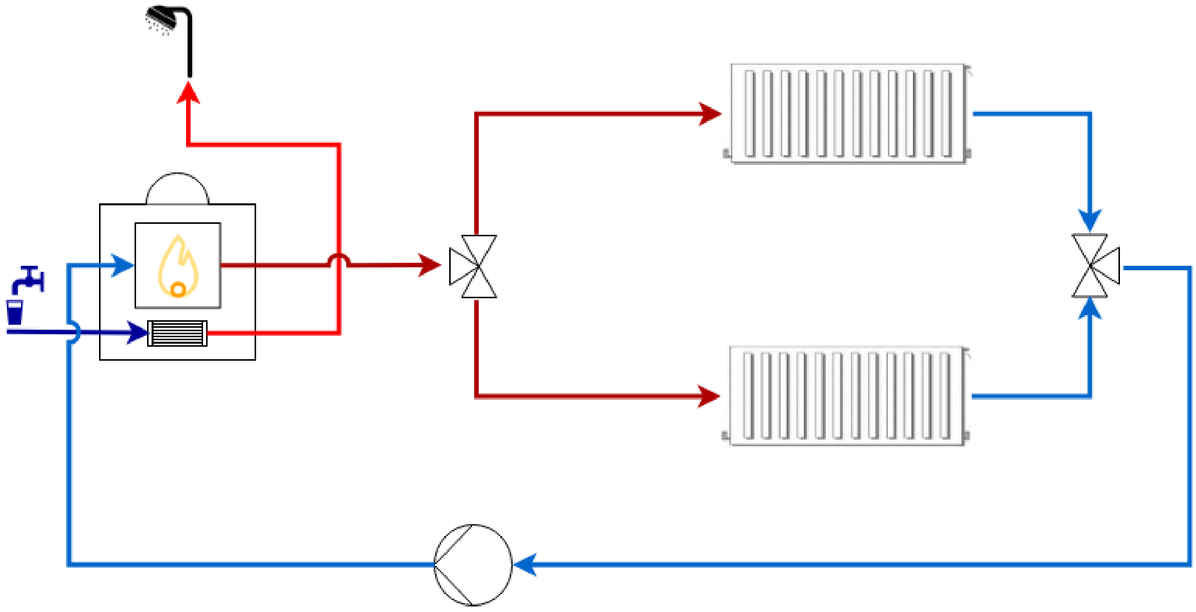


Figure B.2: Set-up of space heating and DHW system for the mono gas boiler cases

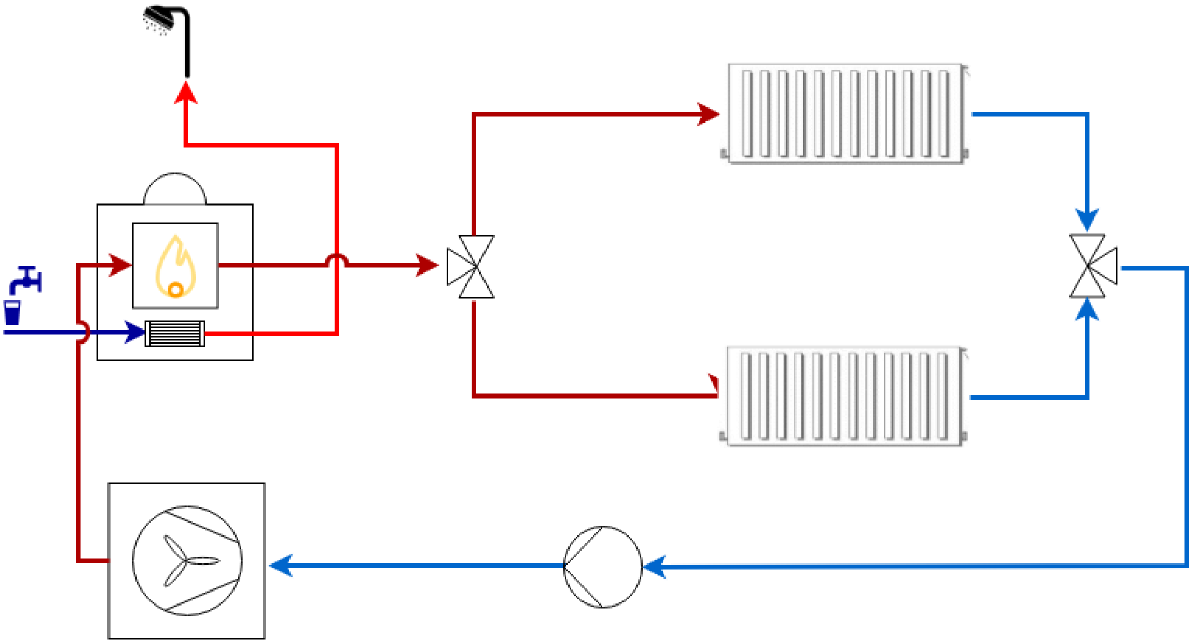


Figure B.3: Set-up of space heating and DHW system for the hybrid heat pump cases

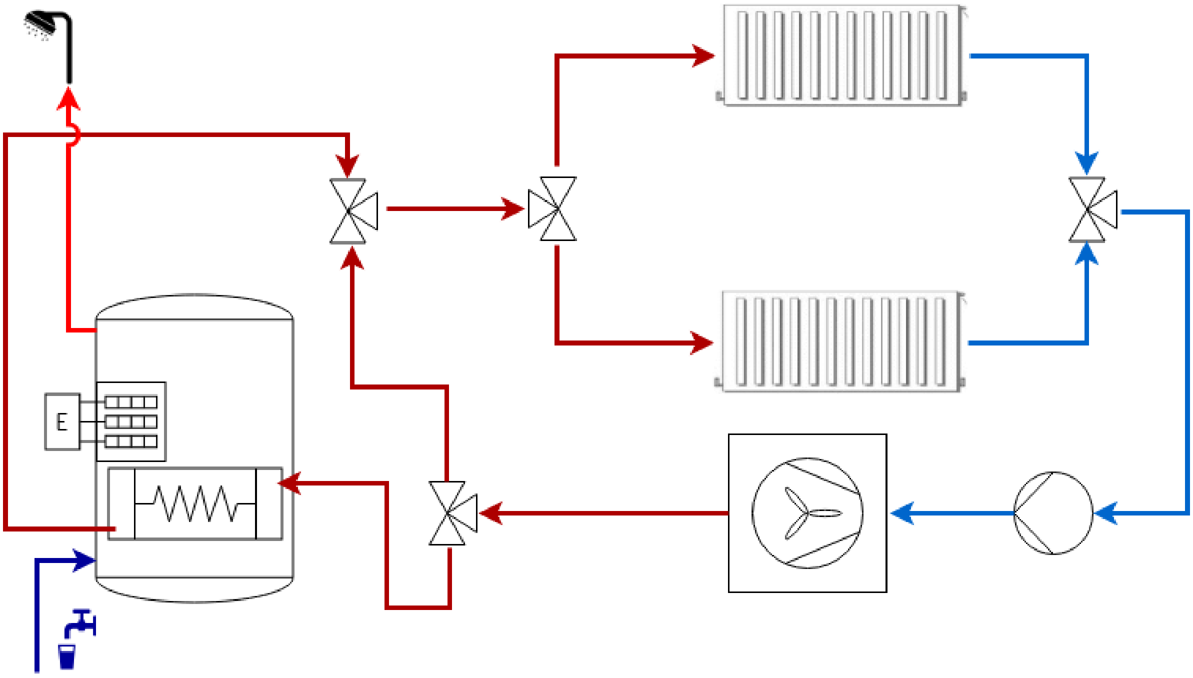


Figure B.4: Set-up of space heating and DHW system for the all-electric cases

Appendix C

Techno-economic assessments

C.1 Used values for investment costs

Table C.1: Investment costs for the heat sources used in the assessments with the corresponding ISDE subsidy. The costs include installation costs and VAT.

Heat sources	Costs [€]	ISDE subsidy [€]	(RVO.nl, 2018)
Tzerra M 24c Plus CW3 19.5 kW combi gas boiler	979	0	(Consumentenbond, n.d.-b)
Itho Daalderop 2.5 kW heat pump	3900	1500	(CVtotaal, n.d.-a)
Techneco Elga 4.9 kW heat pump	4300	1700	(CVtotaal, n.d.-b)
Vaillant aroTHERM split VWL 3.6 kW heat pump	3400	1700	(CVtotaal, n.d.-b; Wasco, n.d.)
Techneco Loria Duo 4 kW heat pump	6925	1700	(KliMate, n.d.-a; Solar Groep, n.d.)
Techneco Loria Duo 6 kW heat pump	7105	1800	(KliMate, n.d.-b; Solar Groep, n.d.)
Techneco Loria Duo 10 kW heat pump	8375	2100	(KliMate, n.d.-c; Solar Groep, n.d.)

Table C.2: Investment costs for the insulation measures used in the assessments of the high insulation level cases. The costs include VAT.

High insulation level	Costs [€]	
Outside façade insulation	8001	(Milieu Centraal, n.d.-c)
Triple glas, including insulating frames	8400	(Milieu Centraal, n.d.-b)
Roof insulation	5200	(Milieu Centraal, n.d.-a)
Floor insulation	1040	(Agentschap NL, 2011)

Table C.3: Investment costs for the insulation measures used in the assessments of the improved insulation level cases. The costs include VAT.

Improved insulation level	Costs [€]	
Cavity wall insulation	850	(Agentschap NL, 2011)
Roof insulation	3470	(Agentschap NL, 2011)
HR++ glass	3620	(Agentschap NL, 2011)
Floor insulation	1040	(Agentschap NL, 2011)

Table C.4: Investment costs for the low temperature radiators used in the assessments of the improved and high insulation levels cases. The costs include VAT.

Low temperature radiators	Costs [€]	
Jaga Briza 4272W Low-H2O LT radiator	1013	(Jaga, 2016)
Jaga Briza 2147W Low-H2O LT radiator	1370	(Jaga, 2016)
Installation costs	540	(CV-kosten.nl, 2018)

Table C.5: Cost reduction factor of investments, relative to the current costs

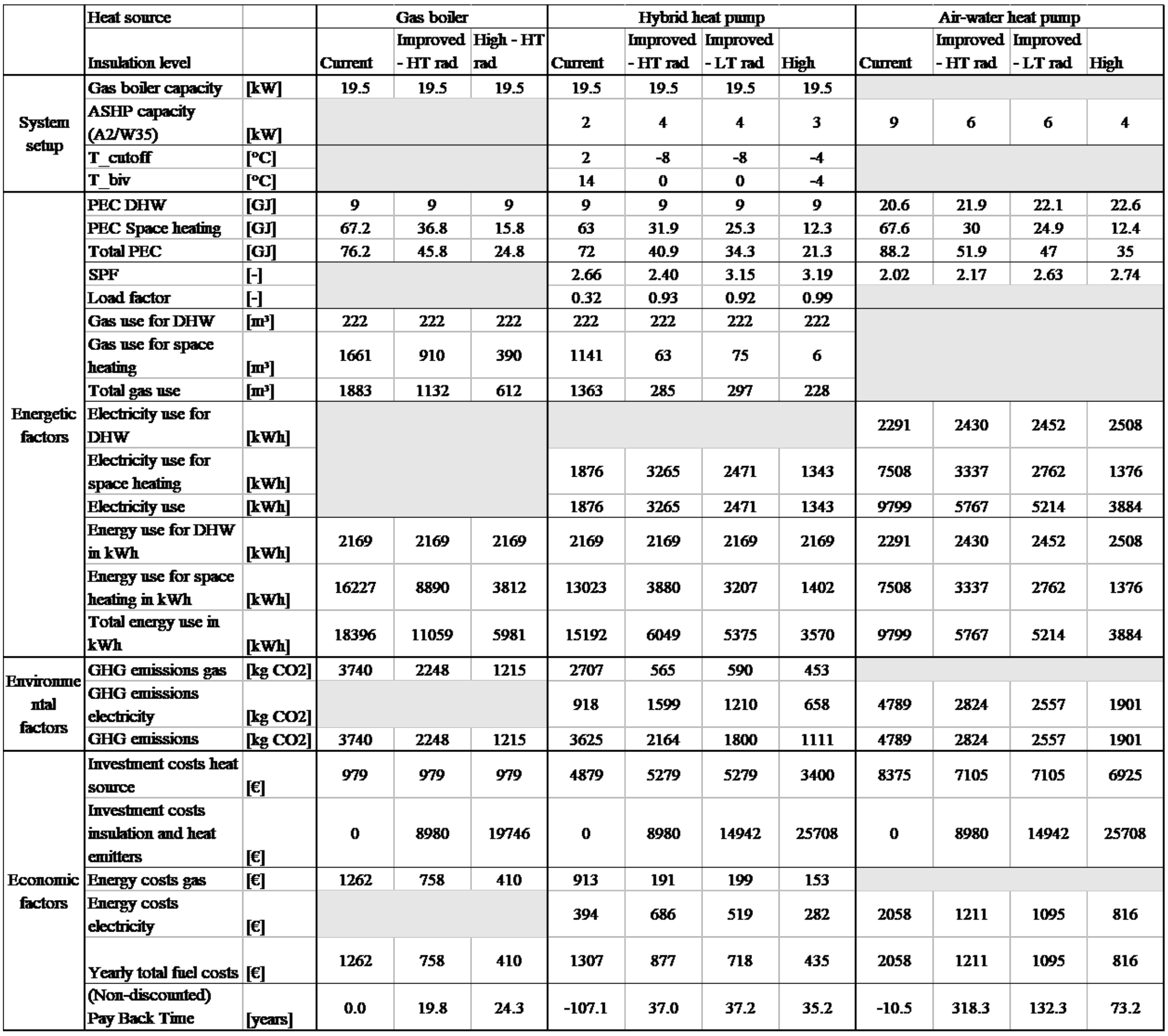
	Cost reduction factor [-]		
	2025	2040	
Heat pump	0.75	0.6	(Naber et al., 2016; van Melle et al., 2015)
Gas boiler	0.9	0.8	(Naber et al., 2016; van Melle et al., 2015)
High insulation level	0.85	0.75	(Naber et al., 2016; van Melle et al., 2015)
Improved insulation level	0.9	0.8	(Naber et al., 2016; van Melle et al., 2015)
Low temperature radiators	0.9	0.8	(Naber et al., 2016)

C.2 Studied design options

Table C.6: Studied design options for the techno-economic assessment of the scenarios

	2025			**2040**		
	Heat source	Insulation level	Heat emission	Heat source	Insulation level	Heat emission
S1a	HHP	Improved	LT	ASHP	Improved	LT
S1b	HHP	High	LT	ASHP	High	LT
S1c	HHP	Current	HT	ASHP	High	LT
S1d	HHP	Improved	HT	ASHP	Improved	LT
S1e	HHP	Current	HT	ASHP	Improved	LT
S1f	HHP	Current	HT	ASHP	Current	HT
S2a	HHP	Current	HT	HHP + green gas	High	LT
S2b	HHP	Current	HT	HHP + green gas	Improved	HT
S2c	HHP	Current	HT	HHP + green gas	Improved	LT
S2d	HHP	Improved	HT	HHP + green gas	Improved	HT
S2e	HHP	Improved	HT	HHP + green gas	Improved	LT
S2f	HHP	Improved	LT	HHP + green gas	Improved	LT
S2g	HHP	Current	HT	HHP + green gas	Current	HT
S2h	HHP	High	LT	HHP + green gas	High	LT
S3a	ASHP	Improved	LT	ASHP	Improved	LT
S3b	ASHP	High	LT	ASHP	High	LT
S3c	ASHP	Current	HT	ASHP	Current	HT
S4a	Gas boiler	Current	HT	ASHP	High	LT
S4b	Gas boiler	Current	HT	Green gas boiler	High	HT
S4c	Gas boiler	Current	HT	Green gas boiler	Improved	HT
S4d	Gas boiler	Current	HT	Green gas boiler	Current	HT
S4e	Gas boiler	High	HT	Green gas boiler	High	HT
S4f	Gas boiler	Current	HT	ASHP	Current	HT
S4g	Gas boiler	High	HT	ASHP	High	LT
S4h	Gas boiler	Improved	HT	Green gas boiler	Improved	HT
S4i	Gas boiler	Improved	HT	ASHP	Improved	LT

C.3 Full table of present-day techno-economic analysis



	Heat source		Gas boiler			Hybrid heat pump				Air-water heat pump			
	Insulation level		Current	Improved - HT rad	High - HT rad	Current	Improved - HT rad	Improved - LT rad	High	Current	Improved - HT rad	Improved - LT rad	High
System setup	Gas boiler capacity	[kW]	19.5	19.5	19.5	19.5	19.5	19.5	19.5				
	ASHP capacity (A2/W35)	[kW]				2	4	4	3	9	6	6	4
	T_cutoff	[°C]				2	-8	-8	-4				
	T_biv	[°C]				14	0	0	-4				
Energetic factors	PEC DHW	[GJ]	9	9	9	9	9	9	9	20.6	21.9	22.1	22.6
	PEC Space heating	[GJ]	67.2	36.8	15.8	63	31.9	25.3	12.3	67.6	30	24.9	12.4
	Total PEC	[GJ]	76.2	45.8	24.8	72	40.9	34.3	21.3	88.2	51.9	47	35
	SPF	[-]				2.66	2.40	3.15	3.19	2.02	2.17	2.63	2.74
	Load factor	[-]				0.32	0.93	0.92	0.99				
	Gas use for DHW	[m³]	222	222	222	222	222	222	222				
	Gas use for space heating	[m³]	1661	910	390	1141	63	75	6				
	Total gas use	[m³]	1883	1132	612	1363	285	297	228				
	Electricity use for DHW	[kWh]								2291	2430	2452	2508
	Electricity use for space heating	[kWh]				1876	3265	2471	1343	7508	3337	2762	1376
	Electricity use	[kWh]				1876	3265	2471	1343	9799	5767	5214	3884
	Energy use for DHW in kWh	[kWh]	2169	2169	2169	2169	2169	2169	2169	2291	2430	2452	2508
	Energy use for space heating in kWh	[kWh]	16227	8890	3812	13023	3880	3207	1402	7508	3337	2762	1376
	Total energy use in kWh	[kWh]	18396	11059	5981	15192	6049	5375	3570	9799	5767	5214	3884
Environmental factors	GHG emissions gas	[kg CO2]	3740	2248	1215	2707	565	590	453				
	GHG emissions electricity	[kg CO2]				918	1599	1210	658	4789	2824	2557	1901
	GHG emissions	[kg CO2]	3740	2248	1215	3625	2164	1800	1111	4789	2824	2557	1901
Economic factors	Investment costs heat source	[€]	979	979	979	4879	5279	5279	3400	8375	7105	7105	6925
	Investment costs insulation and heat emitters	[€]	0	8980	19746	0	8980	14942	25708	0	8980	14942	25708
	Energy costs gas	[€]	1262	758	410	913	191	199	153				
	Energy costs electricity	[€]				394	686	519	282	2058	1211	1095	816
	Yearly total fuel costs	[€]	1262	758	410	1307	877	718	435	2058	1211	1095	816
	(Non-discounted) Pay Back Time	[years]	0.0	19.8	24.3	-107.1	37.0	37.2	35.2	-10.5	318.3	132.3	73.2

Figure C.1: Present-day techno-economic overview of all three models

C.4 Specification of fixed costs electricity and gas

In Section 3.5.2 it is explained which fixed costs for electricity and gas are taken into account and which are not. The studied house is currently assumed to have a 1 x 35 A electricity connection and a G4 gas connection. In case of a switch to an all-electric system it is assumed that the electricity connection will have to be reinforced to 3 x 25 A and that the gas connection is removed (i.e., the household will also switch to cooking on electricity, instead of gas).

It can be seen in Table C.7 that the periodic fixed costs of electricity do not increase with the current tariffs when switching from a 1 x 35 A connection to a larger 3 x 25 A connection. Therefore these costs are not considered in the study. However, the one-off connection costs of the upgrade are considered.

As depicted in Table C.8, all of the periodic fixed costs for gas as well as the one-off disconnection costs are considered when switching to an all-electric system.

Table C.7: Specification of fixed costs electricity, the underlined costs are considered in this study, based on Liander (2018a) and Nuon (n.d.)

Connection type		No all-electric heating system 1 x 35 A	All-electric heating system 3 x 25 A
Periodic fixed costs			
Periodic connection costs electricity	€	19.71	19.71
Standing charge electricity	€	17.99	17.99
Transport capacity costs electricity	€	147.02	147.02
Measuring costs electricity	€	23.51	23.51
Fixed retail costs electricity	€	33.18	33.18
One-off connection costs			
Cost of upgrade to 3 x 25 A	€		200.04

Table C.8: Specification of fixed costs electricity, the underlined costs are considered in this study, based on Liander (2018b) and Nuon (n.d.)

Connection type		No all-electric heating system 1 x 35 A	All-electric heating system 3 x 25 A
Periodic fixed costs			
Periodic connection costs gas	€	29.86	0
Standing charge gas	€	17.99	0
Transport capacity costs gas	€	90.56	0
Measuring costs gas	€	20.95	0
Fixed retail costs gas	€	40.29	0
One-off disconnection costs			
Cost of removal gas connection	€		567.77

Appendix D

Simulation results

D.1 System sizing of ASHP and HHP

D.1.1 System sizing of ASHP

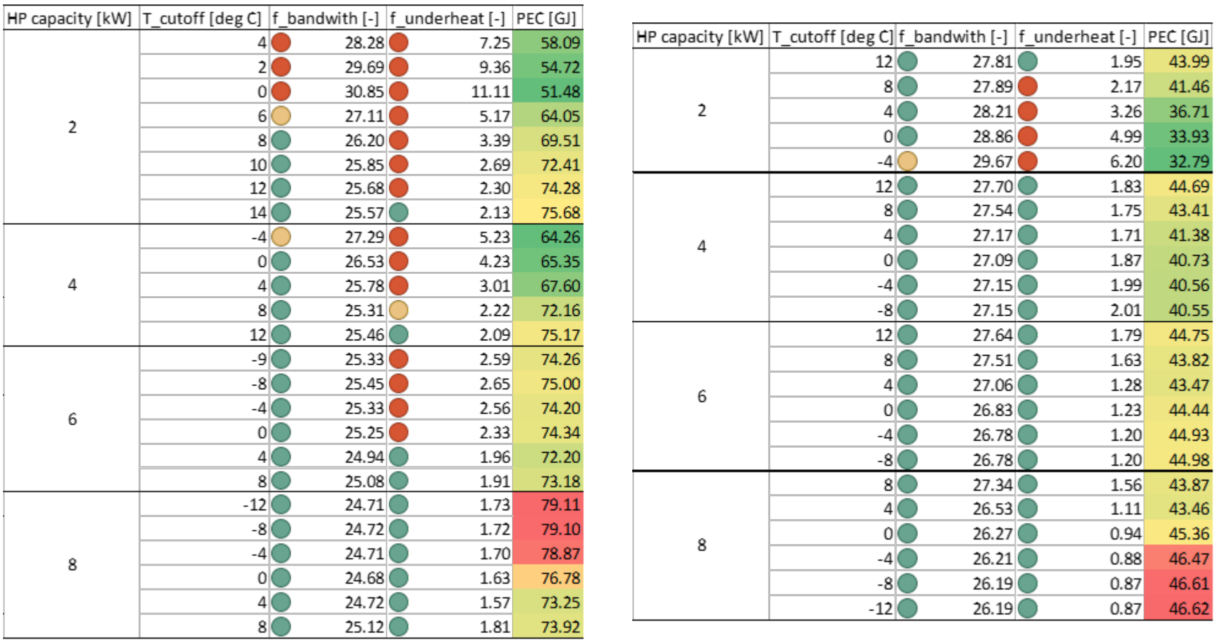
Table D.1: f-factors and primary energy consumption of all-electric heat pump case with different insulation levels

Insulation level	HP capacity [kW]	$f_{underheat}$ [-]	$f_{bandwidth}$ [-]	PEC [GJ]
Current	8	2.2	25.8	86.6
	9	1.8	25.6	88.2
	10	1.6	25.3	87.0
Improved-HT	5	2.0	28.2	51.1
	6	1.5	28.0	51.9
	7	1.3	27.6	52.6
	9	1.0	27.7	53.2
Improved - LT	5	2.1	27.9	46.8
	6	1.5	27.6	47.5
	7	1.3	27.4	47.4
High	3	2.5	40.4	33.9
	4	1.6	40.7	35.0
	5	1.0	41.1	35.8
	6	0.8	41.0	36.1

D.1.2 System sizing of HHP

Figure D.1 displays the HHP simulation results with the bivalent alternative operation mode, for different heat pump capacities and cut-off temperatures.

Figures D.2 to D.5 display the HHP simulation results with the bivalent parallel operation mode, for different heat pump capacities and cut-off temperatures.

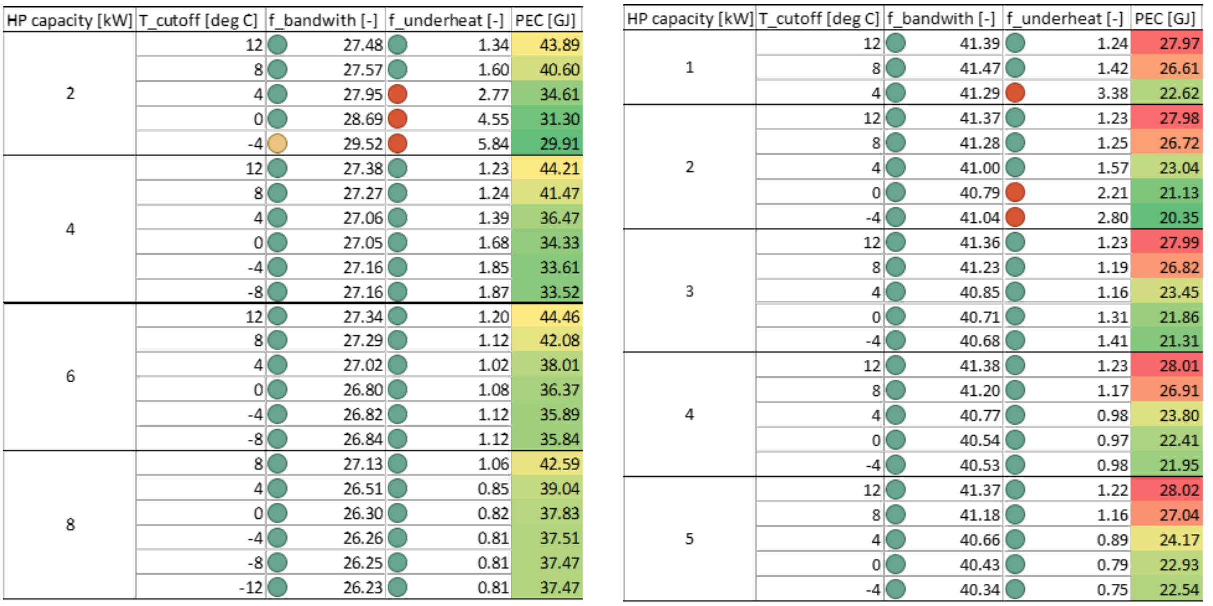


HP capacity [kW]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
2	4	🔴 28.28	🔴 7.25	58.09
	2	🔴 29.69	🔴 9.36	54.72
	0	🔴 30.85	🔴 11.11	51.48
	6	🟡 27.11	🔴 5.17	64.05
	8	🟢 26.20	🔴 3.39	69.51
	10	🟢 25.85	🔴 2.69	72.41
	12	🟢 25.68	🔴 2.30	74.28
	14	🟢 25.57	🟢 2.13	75.68
4	-4	🟡 27.29	🔴 5.23	64.26
	0	🟢 26.53	🔴 4.23	65.35
	4	🟢 25.78	🔴 3.01	67.60
	8	🟢 25.31	🟡 2.22	72.16
	12	🟢 25.46	🟢 2.09	75.17
6	-9	🟢 25.33	🔴 2.59	74.26
	-8	🟢 25.45	🔴 2.65	75.00
	-4	🟢 25.33	🔴 2.56	74.20
	0	🟢 25.25	🔴 2.33	74.34
	4	🟢 24.94	🟢 1.96	72.20
	8	🟢 25.08	🟢 1.91	73.18
8	-12	🟢 24.71	🟢 1.73	79.11
	-8	🟢 24.72	🟢 1.72	79.10
	-4	🟢 24.71	🟢 1.70	78.87
	0	🟢 24.68	🟢 1.63	76.78
	4	🟢 24.72	🟢 1.57	73.25
	8	🟢 25.12	🟢 1.81	73.92

(a) Current insulation level

HP capacity [kW]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
2	12	🟢 27.81	🟢 1.95	43.99
	8	🟢 27.89	🔴 2.17	41.46
	4	🟢 28.21	🔴 3.26	36.71
	0	🟢 28.86	🔴 4.99	33.93
	-4	🟡 29.67	🔴 6.20	32.79
4	12	🟢 27.70	🟢 1.83	44.69
	8	🟢 27.54	🟢 1.75	43.41
	4	🟢 27.17	🟢 1.71	41.38
	0	🟢 27.09	🟢 1.87	40.73
	-4	🟢 27.15	🟢 1.99	40.56
	-8	🟢 27.15	🟢 2.01	40.55
6	12	🟢 27.64	🟢 1.79	44.75
	8	🟢 27.51	🟢 1.63	43.82
	4	🟢 27.06	🟢 1.28	43.47
	0	🟢 26.83	🟢 1.23	44.44
	-4	🟢 26.78	🟢 1.20	44.93
	-8	🟢 26.78	🟢 1.20	44.98
8	8	🟢 27.34	🟢 1.56	43.87
	4	🟢 26.53	🟢 1.11	43.46
	0	🟢 26.27	🟢 0.94	45.36
	-4	🟢 26.21	🟢 0.88	46.47
	-8	🟢 26.19	🟢 0.87	46.61
	-12	🟢 26.19	🟢 0.87	46.62

(b) Improved insulation level with HT radiators



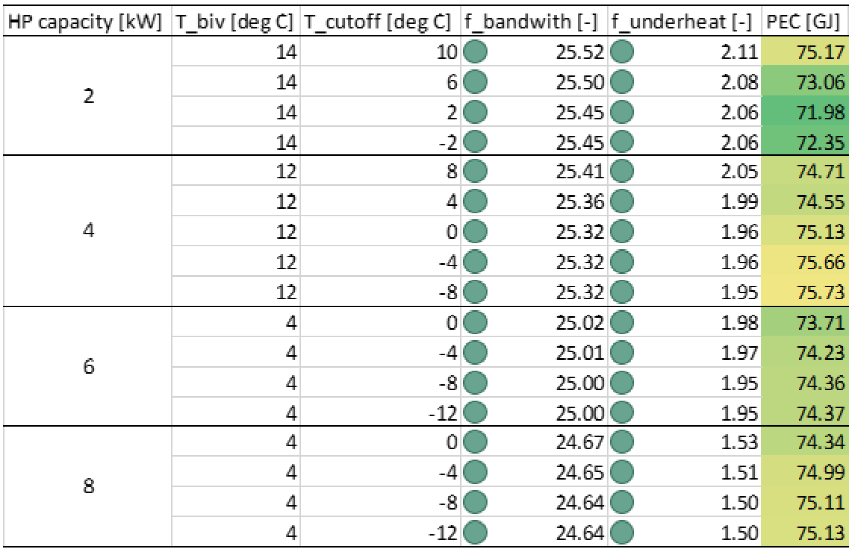
HP capacity [kW]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
2	12	🟢 27.48	🟢 1.34	43.89
	8	🟢 27.57	🟢 1.60	40.60
	4	🟢 27.95	🔴 2.77	34.61
	0	🟢 28.69	🔴 4.55	31.30
	-4	🟡 29.52	🔴 5.84	29.91
4	12	🟢 27.38	🟢 1.23	44.21
	8	🟢 27.27	🟢 1.24	41.47
	4	🟢 27.06	🟢 1.39	36.47
	0	🟢 27.05	🟢 1.68	34.33
	-4	🟢 27.16	🟢 1.85	33.61
	-8	🟢 27.16	🟢 1.87	33.52
6	12	🟢 27.34	🟢 1.20	44.46
	8	🟢 27.29	🟢 1.12	42.08
	4	🟢 27.02	🟢 1.02	38.01
	0	🟢 26.80	🟢 1.08	36.37
	-4	🟢 26.82	🟢 1.12	35.89
	-8	🟢 26.84	🟢 1.12	35.84
8	8	🟢 27.13	🟢 1.06	42.59
	4	🟢 26.51	🟢 0.85	39.04
	0	🟢 26.30	🟢 0.82	37.83
	-4	🟢 26.26	🟢 0.81	37.51
	-8	🟢 26.25	🟢 0.81	37.47
	-12	🟢 26.23	🟢 0.81	37.47

(c) Improved insulation level with LT radiators

HP capacity [kW]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
1	12	🟢 41.39	🟢 1.24	27.97
	8	🟢 41.47	🟢 1.42	26.61
	4	🟢 41.29	🔴 3.38	22.62
2	12	🟢 41.37	🟢 1.23	27.98
	8	🟢 41.28	🟢 1.25	26.72
	4	🟢 41.00	🟢 1.57	23.04
	0	🟢 40.79	🔴 2.21	21.13
	-4	🟢 41.04	🔴 2.80	20.35
3	12	🟢 41.36	🟢 1.23	27.99
	8	🟢 41.23	🟢 1.19	26.82
	4	🟢 40.85	🟢 1.16	23.45
	0	🟢 40.71	🟢 1.31	21.86
	-4	🟢 40.68	🟢 1.41	21.31
4	12	🟢 41.38	🟢 1.23	28.01
	8	🟢 41.20	🟢 1.17	26.91
	4	🟢 40.77	🟢 0.98	23.80
	0	🟢 40.54	🟢 0.97	22.41
	-4	🟢 40.53	🟢 0.98	21.95
5	12	🟢 41.37	🟢 1.22	28.02
	8	🟢 41.18	🟢 1.16	27.04
	4	🟢 40.66	🟢 0.89	24.17
	0	🟢 40.43	🟢 0.79	22.93
	-4	🟢 40.34	🟢 0.75	22.54

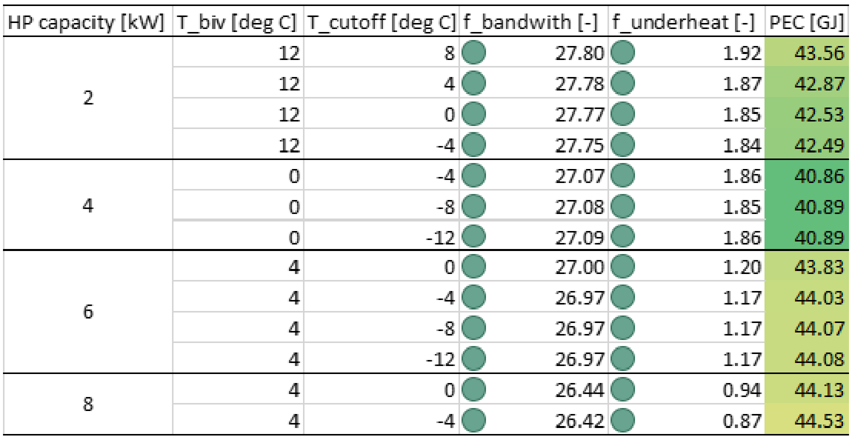
(d) High insulation level

Figure D.1: HHP simulation results with bivalent alternative operation mode, for different heat pump capacities and cut-off temperatures



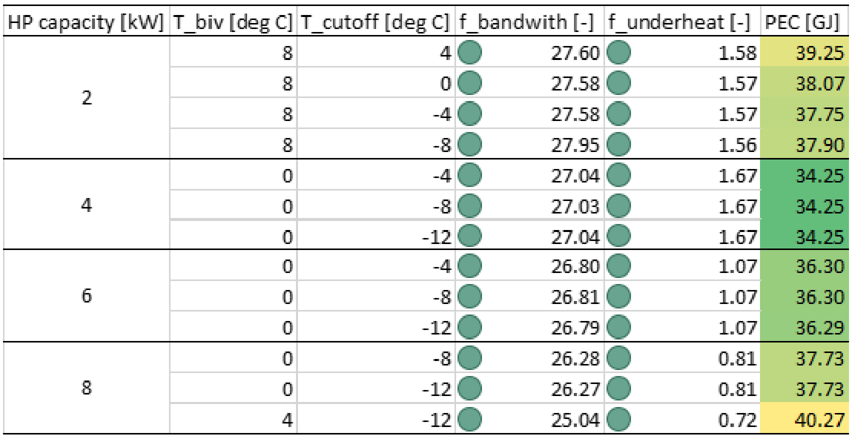
HP capacity [kW]	T_biv [deg C]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
2	14	10	● 25.52	● 2.11	75.17
	14	6	● 25.50	● 2.08	73.06
	14	2	● 25.45	● 2.06	71.98
	14	-2	● 25.45	● 2.06	72.35
4	12	8	● 25.41	● 2.05	74.71
	12	4	● 25.36	● 1.99	74.55
	12	0	● 25.32	● 1.96	75.13
	12	-4	● 25.32	● 1.96	75.66
	12	-8	● 25.32	● 1.95	75.73
6	4	0	● 25.02	● 1.98	73.71
	4	-4	● 25.01	● 1.97	74.23
	4	-8	● 25.00	● 1.95	74.36
	4	-12	● 25.00	● 1.95	74.37
8	4	0	● 24.67	● 1.53	74.34
	4	-4	● 24.65	● 1.51	74.99
	4	-8	● 24.64	● 1.50	75.11
	4	-12	● 24.64	● 1.50	75.13

Figure D.2: Current insulation level



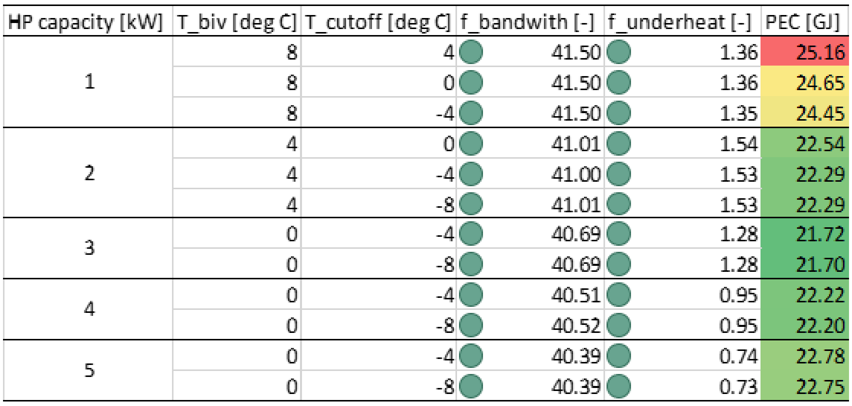
HP capacity [kW]	T_biv [deg C]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
2	12	8	● 27.80	● 1.92	43.56
	12	4	● 27.78	● 1.87	42.87
	12	0	● 27.77	● 1.85	42.53
	12	-4	● 27.75	● 1.84	42.49
4	0	-4	● 27.07	● 1.86	40.86
	0	-8	● 27.08	● 1.85	40.89
	0	-12	● 27.09	● 1.86	40.89
6	4	0	● 27.00	● 1.20	43.83
	4	-4	● 26.97	● 1.17	44.03
	4	-8	● 26.97	● 1.17	44.07
	4	-12	● 26.97	● 1.17	44.08
8	4	0	● 26.44	● 0.94	44.13
	4	-4	● 26.42	● 0.87	44.53

Figure D.3: Improved insulation level with HT radiators



HP capacity [kW]	T_biv [deg C]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
2	8	4	● 27.60	● 1.58	39.25
	8	0	● 27.58	● 1.57	38.07
	8	-4	● 27.58	● 1.57	37.75
	8	-8	● 27.95	● 1.56	37.90
4	0	-4	● 27.04	● 1.67	34.25
	0	-8	● 27.03	● 1.67	34.25
	0	-12	● 27.04	● 1.67	34.25
6	0	-4	● 26.80	● 1.07	36.30
	0	-8	● 26.81	● 1.07	36.30
	0	-12	● 26.79	● 1.07	36.29
8	0	-8	● 26.28	● 0.81	37.73
	0	-12	● 26.27	● 0.81	37.73
	4	-12	● 25.04	● 0.72	40.27

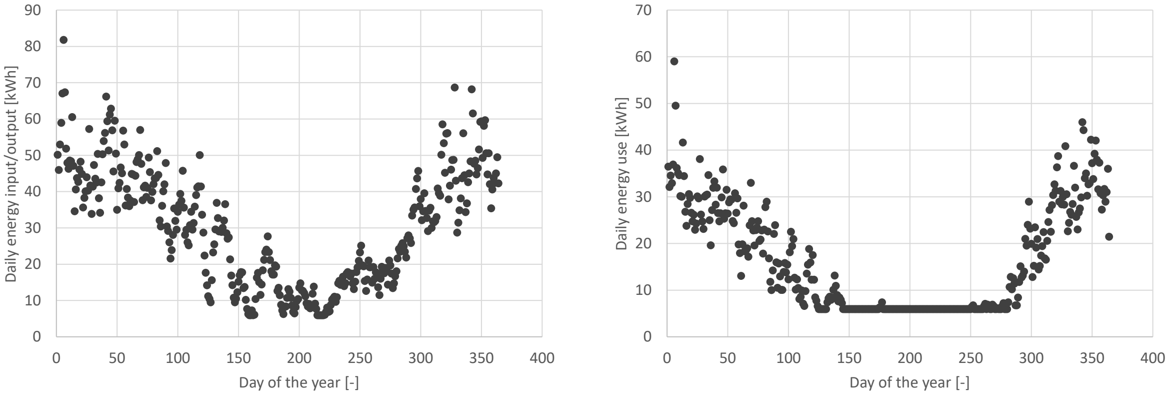
Figure D.4: Improved insulation level with LT radiators



HP capacity [kW]	T_biv [deg C]	T_cutoff [deg C]	f_bandwith [-]	f_underheat [-]	PEC [GJ]
1	8	4	● 41.50	● 1.36	25.16
	8	0	● 41.50	● 1.36	24.65
	8	-4	● 41.50	● 1.35	24.45
2	4	0	● 41.01	● 1.54	22.54
	4	-4	● 41.00	● 1.53	22.29
	4	-8	● 41.01	● 1.53	22.29
3	0	-4	● 40.69	● 1.28	21.72
	0	-8	● 40.69	● 1.28	21.70
4	0	-4	● 40.51	● 0.95	22.22
	0	-8	● 40.52	● 0.95	22.20
5	0	-4	● 40.39	● 0.74	22.78
	0	-8	● 40.39	● 0.73	22.75

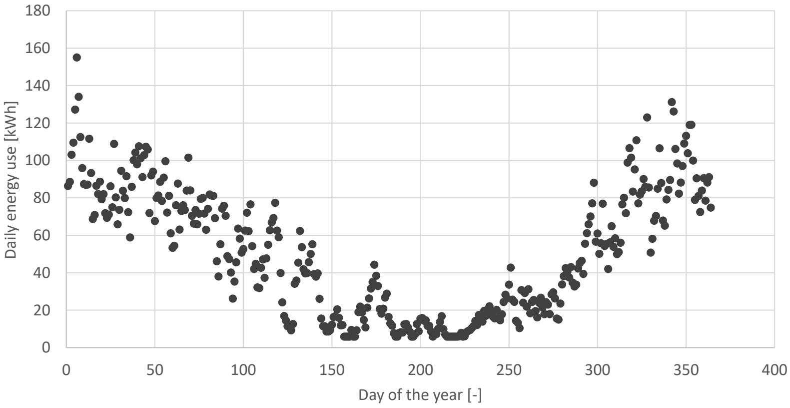
Figure D.5: High insulation level

D.2 Daily energy supply and use graphs over the whole year



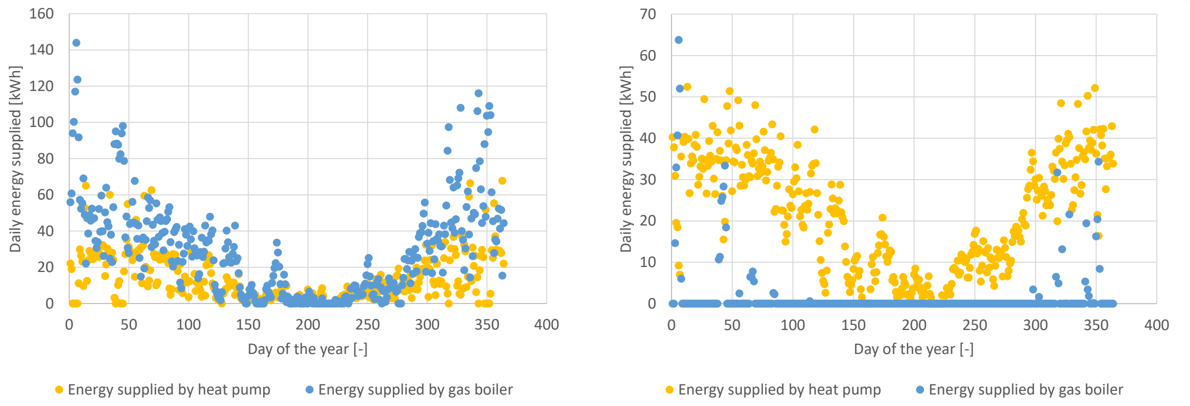
(a) Improved insulation level

(b) High insulation level



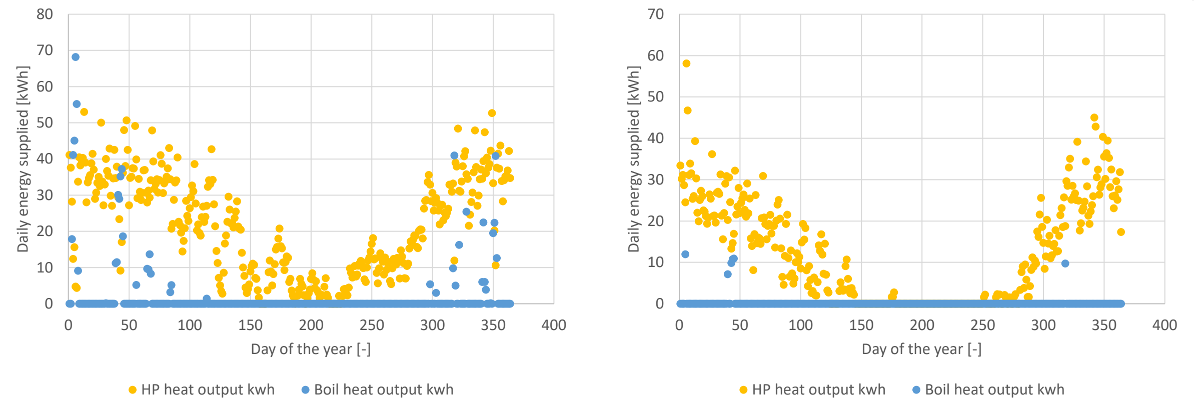
(c) Current insulation level

Figure D.6: Energy use by the mono gas boiler system, for the three considered insulation levels



(a) Current insulation level

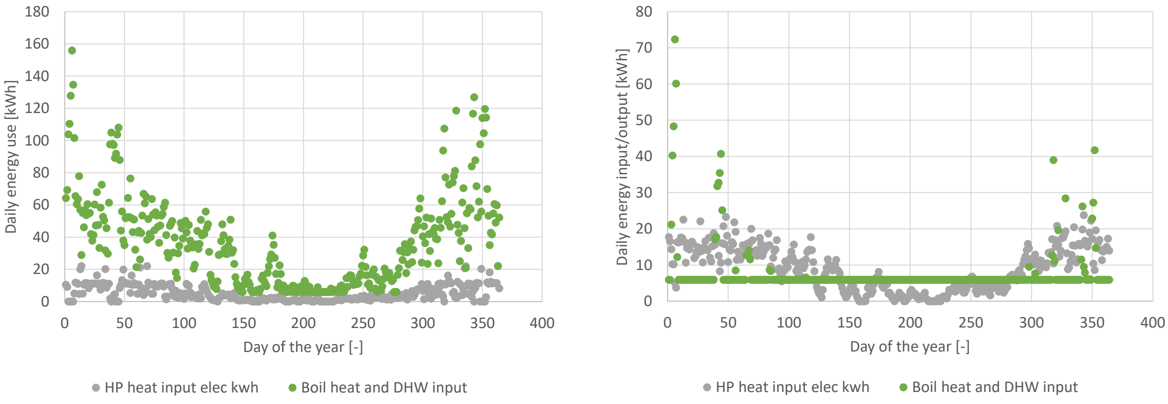
(b) Improved-HT insulation level



(c) Improved-LT insulation level

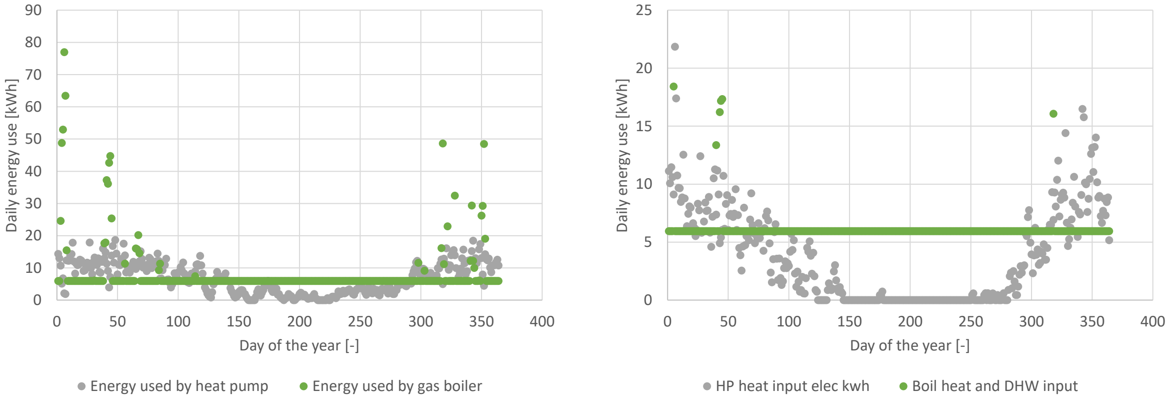
(d) High insulation level

Figure D.7: Energy supplied by the hybrid heat pump system, for the four considered insulation levels



(a) Current insulation level

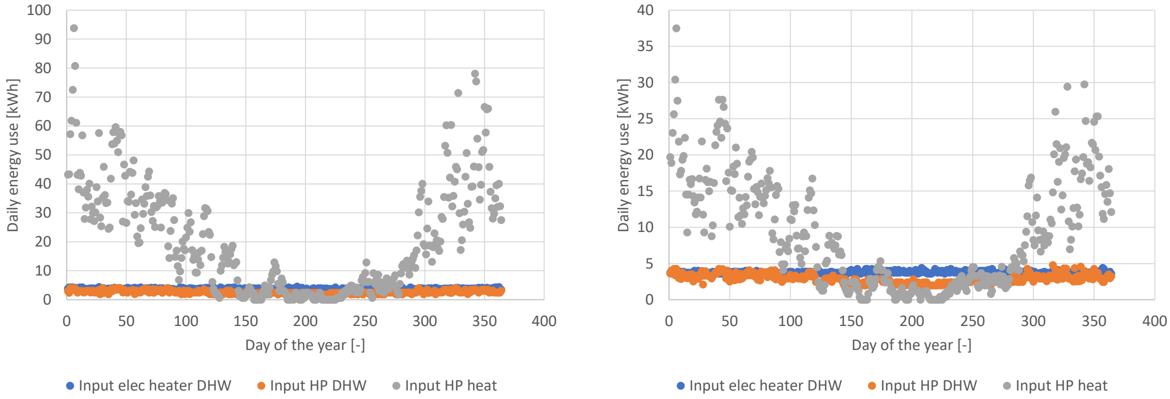
(b) Improved-HT insulation level



(c) Improved-LT insulation level

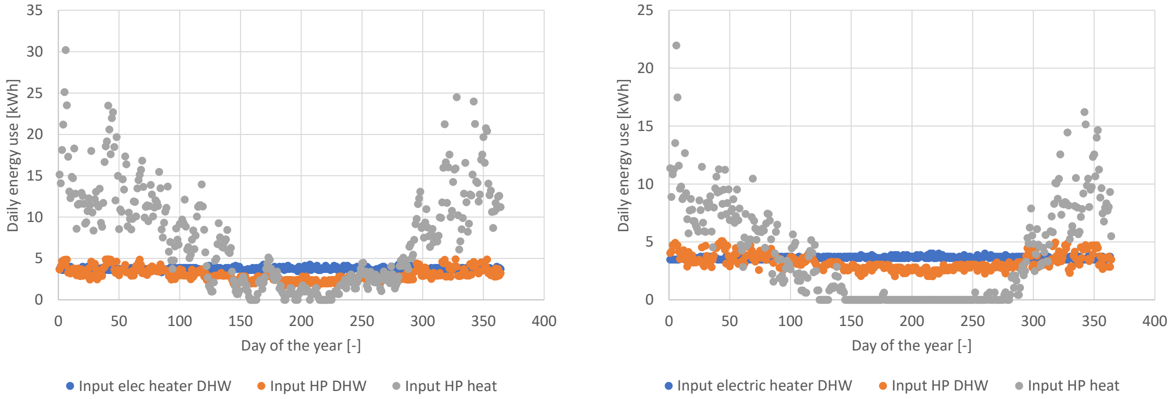
(d) High insulation level

Figure D.8: Energy use of the hybrid heat pump system, for the four considered insulation levels



(a) Current insulation level

(b) Improved-HT insulation level



(c) Improved-LT insulation level

(d) High insulation level

Figure D.9: Energy use of the all-electric air-source heat pump system, for the four considered insulation levels

Appendix E

Interviewees and expert workshop

E.1 List of interviewees

Table E.1: List of interviewees

Interviewee number	Function	Organization	Type
1	Strategic advisor built environment	Gasunie	Gas network operator (TSO)
2	Senior advisor renewable heating and cooling	Netherlands Enterprice Agency (RVO.nl)	Government
3	Policy advisor spacial development	Municipality of Nijmegen	Government
4	Manager innovative technologies	Remeha	Gas boiler manufacturer
5	Policy advisor energy	Vereniging Eigen Huis	Home owners association
6	Architectural specialist	Vereniging Eigen Huis	Home owners association
7	Specialist technology and market	UNETO-VNI	Business organization installation sector
8	Program manager energy	UNETO-VNI	Business organization installation sector
9	Director	Techneco	Heat pump supplier and producer
10	Project manager	Enexis (Enpuls)	Distribution system operator (DSO)

E.2 List of workshop attendees

Table E.2: List of expert workshop attendees

Attendee number	Function	Organization
1	Member energy transition team	Gasunie
2	Senior consultant energy systems	Royal HaskoningDHV
3	Junior consultant environment & energy	Royal HaskoningDHV
4	Proffessor system innovations & sustainability transitions	Eindhoven University of Technology
5	Student Innovation Sciences	Eindhoven University of Technology
6	Student Innovation Sciences & Sustainable Energy Technology	Eindhoven University of Technology
7	Engineer sustainable energy systems	Eneco
8	Specialist	Stedin
9	Researcher waste, energy saving and installations	Milieu Centraal
10	Manager innovative technologies	Remeha
11	Specialist	RVO.nl
12	Consultant	Business Development Holland
13	Director	Techneco
14	Project manager real estate	Talis
15	Project manager sustainability	Talis
16	Advisor soil and energy	Gemeente Nijmegen

E.3 Report of expert workshop

From the feedback received from the expert workshop, four main feedback points can be deduced. The feedback was acquired by forming three groups of around six attendees with each one moderator/secretary. The groups reviewed the scenarios on their desirability and probability after having read the elaborated scenarios. This exercise was repeated after the presentation of the techno-economic assessment of the scenarios. The workshop was ended with a plenary discussion.

The first main feedback point was that the indicator used for choosing the preferred design option for the home owner should not be the carbon reduction cost but should rather only take costs into account. CO_2 emissions are only relevant for the policy maker and much less for the average home-owner. Therefore, the total yearly costs was used as an indicator to decide on the preferred design options for the home owner.

The second main feedback point was that the step switch of 0 % green gas to 100 % green gas in 2040 resulted in an uneven playing field when comparing the scenarios. When a gradual increase of the green gas ratio is assumed, the CO_2 emissions related to the scenarios that use gas will be lower because a part of the natural gas in the gas mix would already have been substituted by green gas. Therefore, the development of green gas in gas mix was changed from a step switch to a gradual increase.

The third main feedback point was that the insulation costs reported in grey literature for building renovations of existing Dutch houses are underestimated. It was voiced that the real insulation costs for home-owners can possibly be significantly higher than those reported in grey literature. Therefore, a sensitivity analysis was performed where the insulation costs were increased by 50 %.

The fourth main feedback point was regarding the probability of the four scenarios. A consensus was found that the most likely scenario would be one where the goal to have a fully renewable heating and DHW system will not be reached. However, the four scenarios used in this study were scoped to all reach this goal, which was not changed.

Appendix F

Results of techno-economic analyses

F.1 Techno-economic impact of scenarios

Table F.1: Techno-economic impact of S1

		S1a	S1b	S1c	S1d	S1e	S1f
Investment costs heat source	[thousand €]	8	8	8	8	8	9
Investment costs insulation and heat emitter	[thousand €]	13	25	22	13	12	0
Total investment costs	[thousand €]	22	32	30	21	20	9
Energy costs gas	[thousand €]	16	14	34	15	34	34
Fixed costs gas	[thousand €]	5	5	5	5	5	5
Fuel costs electricity	[thousand €]	20	13	15	22	18	28
Extra fixed costs electricity	[€]	240	240	240	240	240	240
Total energy costs	[thousand €]	35	27	48	37	51	62
Non-discounted total costs	[thousand €]	62	65	83	64	77	76
Discounted total costs	[thousand €]	40	45	48	40	45	44
Yearly energy costs 2018-2050 summed	[thousand €]	56	59	65	60	64	70
Primary energy electricity	[GJ]	120	70	90	150	100	140
Primary energy gas	[GJ]	680	640	1210	670	1210	1210
Total primary energy	[GJ]	800	720	1300	820	1310	1350
CO2 emissions electricity	[tonnes]	9	5	7	11	7	10
CO2 emissions gas	[tonnes]	33	32	60	33	60	60
Total CO2 emissions	[tonnes]	42	37	66	44	67	69
Carbon reduction cost	[€/kg]	0.69	0.68	1.13	0.75	1.12	1.28

Table F.2: Techno-economic impact of S2

		S2a	S2b	S2c	S2d	S2e	S2f	S2g	S2h
Investment costs heat source	[thousand €]	7	7	7	8	8	8	7	6
Investment costs insulation and heat emitter	[thousand €]	22	7	12	8	13	13	0	25
Total investment costs	[thousand €]	28	14	19	16	20	21	7	31
Energy costs gas	[thousand €]	38	39	40	21	21	22	61	19
Fixed costs gas	[thousand €]	8	8	8	8	8	8	8	8
Fuel costs electricity	[thousand €]	9	13	11	17	16	13	10	7
Extra fixed costs electricity	[€]	0	0	0	0	0	0	0	0
Total energy costs	[thousand €]	47	53	51	38	37	35	71	26
Non-discounted total costs	[thousand €]	83	75	78	62	65	64	86	65
Discounted total costs	[thousand €]	48	43	45	39	40	41	47	44
Yearly energy costs 2018-2050 summed	[thousand €]	62	62	62	53	54	55	77	56
Primary energy electricity	[GJ]	80	90	80	140	130	110	80	60
Primary energy gas	[GJ]	1240	1510	1510	710	710	720	1400	670
Total primary energy	[GJ]	1320	1600	1600	850	850	820	1480	730
CO2 emissions electricity	[tonnes]	5	6	6	10	10	8	6	4
CO2 emissions gas	[tonnes]	61	62	62	35	35	35	69	33
Total CO2 emissions	[tonnes]	67	68	68	45	45	43	75	37
Carbon reduction cost	[€/kg]	1.09	1.11	1.12	0.67	0.68	0.68	1.58	0.65

Table F.3: Techno-economic impact of S3

		S3a	S3b	S3c
Investment costs heat source	[thousand €]	10	9	11
Investment costs insulation and heat emitter	[thousand €]	13	26	0
Total investment costs	[thousand €]	23	35	11
Energy costs gas	[thousand €]	11	11	11
Fixed costs gas	[thousand €]	2	2	2
Fuel costs electricity	[thousand €]	28	21	52
Extra fixed costs electricity	[€]	240	240	240
Total energy costs	[thousand €]	38	31	62
Non-discounted total costs	[thousand €]	63	68	76
Discounted total costs	[thousand €]	41	47	44
Yearly energy costs 2018-2050 summed	[thousand €]	60	65	73
Primary energy electricity	[GJ]	220	170	420
Primary energy gas	[GJ]	530	530	530
Total primary energy	[GJ]	750	690	940
CO2 emissions electricity	[tonnes]	16	12	30
CO2 emissions gas	[tonnes]	26	26	26
Total CO2 emissions	[tonnes]	42	38	56
Carbon reduction cost	[€/kg]	0.74	0.76	1.07

Table F.4: Techno-economic impact of S4

		S4a	S4b	S4c	S4d	S4e	S4f	S4g	S4h	S4i
Investment costs heat source	[thousand €]	5	2	2	2	2	6	5	2	5
Investment costs insulation and heat emitter	[thousand €]	22	22	7	0	19	0	24	8	13
Total investment costs	[thousand €]	27	23	9	2	21	6	29	10	18
Energy costs gas	[thousand €]	42	55	65	81	33	42	21	53	30
Fixed costs gas	[thousand €]	5	8	8	8	8	5	5	8	5
Fuel costs electricity	[thousand €]	9	0	0	0	0	23	9	0	12
Extra fixed costs electricity	[€]	240	0	0	0	0	240	240	0	240
Total energy costs	[thousand €]	51	55	65	81	33	65	30	53	42
Non-discounted total costs	[thousand €]	84	86	82	90	62	77	65	70	65
Discounted total costs	[thousand €]	47	48	45	48	41	43	42	41	40
Yearly energy costs 2018-2050 summed	[thousand €]	65	66	70	82	54	70	55	62	56
Primary energy electricity	[GJ]	30	0	0	0	0	70	30	0	40
Primary energy gas	[GJ]	1470	1560	1630	1740	920	1470	830	1250	1090
Total primary energy	[GJ]	1500	1560	1630	1740	920	1540	860	1250	1130
CO2 emissions electricity	[tonnes]	2	0	0	0	0	5	2	0	3
CO2 emissions gas	[tonnes]	72	77	80	85	45	72	41	62	54
Total CO2 emissions	[tonnes]	74	77	80	85	45	77	43	62	56
Carbon reduction cost	[€/kg]	1.32	1.4	1.61	2.15	0.69	1.51	0.69	1	0.84

Table F.5: Techno-economic impact of business-as-usual/reference case

		Business-as-usual
Investment costs heat source	[thousand €]	2
Investment costs insulation and heat emitter	[thousand €]	0
Total investment costs	[thousand €]	2
Energy costs gas	[thousand €]	60
Fixed costs gas	[thousand €]	8
Fuel costs electricity	[thousand €]	0
Extra fixed costs electricity	[€]	0
Total energy costs	[thousand €]	60
Non-discounted total costs	[thousand €]	70
Discounted total costs	[thousand €]	39
Yearly energy costs 2018-2050 summed	[thousand €]	62
Primary energy electricity	[GJ]	0
Primary energy gas	[GJ]	2510
Total primary energy	[GJ]	2510
CO2 emissions electricity	[tonnes]	0
CO2 emissions gas	[tonnes]	124
Total CO2 emissions	[tonnes]	124

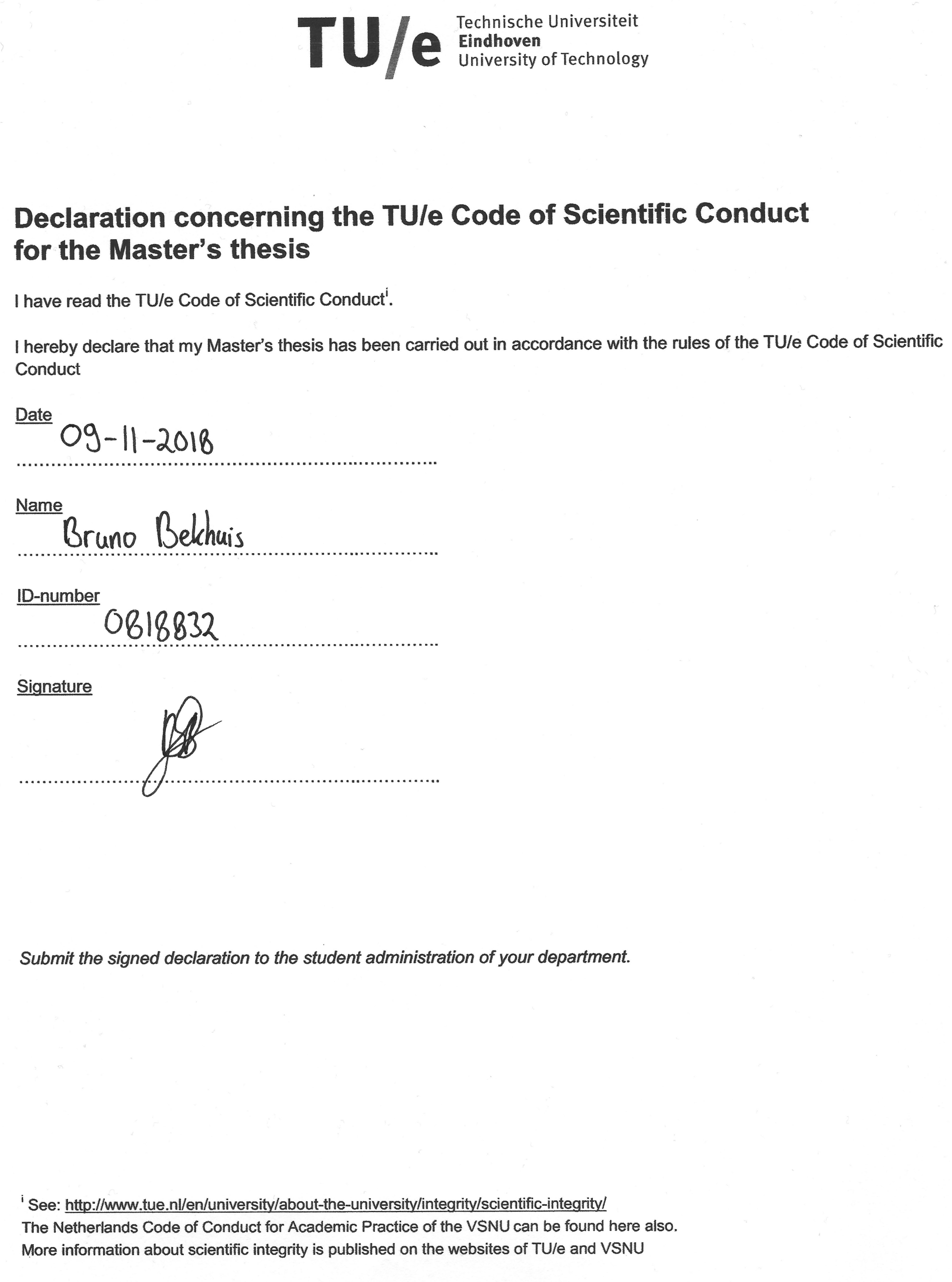
F.2 Green gas price sensitivity results

Table F.6: Results of sensitivity analysis on the price development of green gas

Price development green gas:		Low				Original				High			
		S1a	S2d	S3a	S4e	S1a	S2d	S3a	S4e	S1a	S2d	S3a	S4e
Total energy costs	[thousand €]	35	36	38	28	35	38	38	33	36	41	38	39
Discounted total costs	[thousand €]	39	37	41	38	40	38	41	40	41	40	41	43
Yearly costs summed	[thousand €]	55	50	60	48	56	53	60	54	56	56	60	60
Carbon reduction cost	[€/kg]	0.7	0.6	0.7	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8

Appendix G

Declaration code of scientific conduct



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Declaration concerning the TU/e Code of Scientific Conduct for the Master's thesis

I have read the TU/e Code of Scientific Conduct[i].

I hereby declare that my Master's thesis has been carried out in accordance with the rules of the TU/e Code of Scientific Conduct

Date
09-11-2018

Name
Bruno Bekhuis

ID-number
0818832

Signature

Submit the signed declaration to the student administration of your department.

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[i] See: http://www.tue.nl/en/university/about-the-university/integrity/scientific-integrity/
The Netherlands Code of Conduct for Academic Practice of the VSNU can be found here also.
More information about scientific integrity is published on the websites of TU/e and VSNU