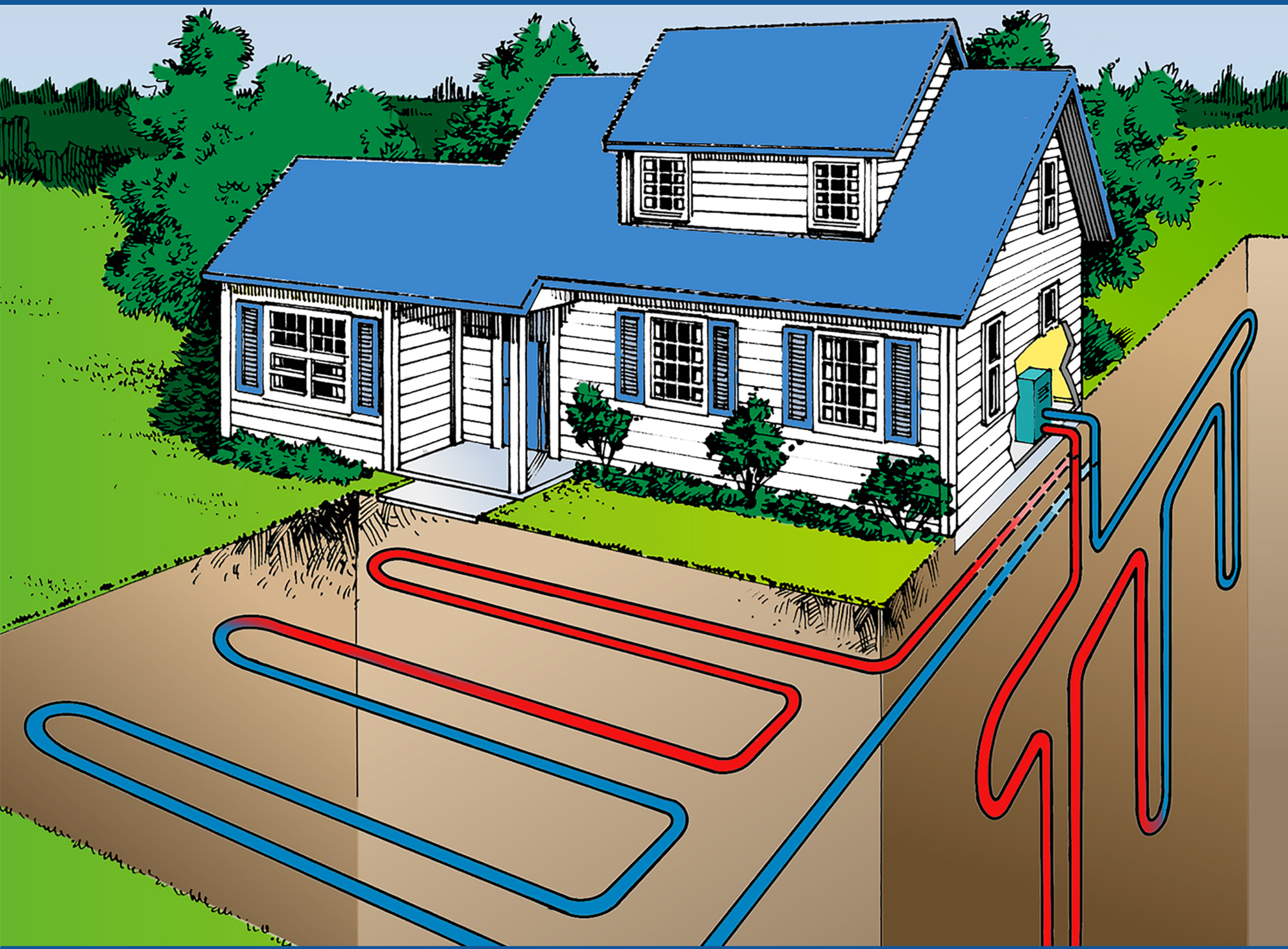
The Influence of Financial Incentives on the Adoption of Heat Pumps in the Netherlands

A Diffusion study using Agent Based Modelling



Master Thesis

Ron Swart

Colophon

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of Master of Science in Complex Systems Engineering and Management

Faculty of Technology, Policy and Management

Title: *The Influence of Financial Incentives on Adoption of Heat Pumps in the Netherlands*

Sub-title: *A diffusion study using Agent Based Modelling*

Location: Delft

Date: October 20th 2017

Pages: 152

Status: Final version

To be defended in public on November 3rd, 2017

Author

Name: Ron Pieter Swart

Student number: 4105745

Email: swart.ron@gmail.com

Graduation Committee

Delft University of Technology	Chair:	Prof. dr. ir. P.M. Herder, section E&I
	First supervisor:	Dr. Msc. N. Mouter, section T&L
	Second supervisor:	Dr. ir. E.J.L. Chappin, section E&I
Delft University of Technology	External supervisor:	Dr. T.W. Fens, section ETI
Alliander	External Supervisor:	A.J. Zondervan

Preface

Dear reader,

Eight months ago I started this project, the last stage of my study in Delft, not knowing the challenges that were waiting. Although there were some stressful times, I truly enjoyed the time working on this project, at both Alliander and the TU Delft. This thesis would not have been possible without the support of my professional and personal circles.

First I would like to thank my graduation committee. Beginning with my first supervisor Dr. T.W. (Theo) Fens, who was the reason I started looking into heat pumps in the first place. I thank Theo as well for the many times we talked, the critical and also quick feedback. I also thank Dr. Mr. N. (Niek) Mouter MSc for his help on the economic aspects of the thesis and helping find a suitable direction of the research. I thank Dr.ir. E.J.L. (Emile) Chappin for helping me with everything concerning ABM, from the emergent behaviour I expect to the experimental setup. I also want to thank Prof.dr.ir. P.M. (Paulien) Herder as chair of my committee for her feedback during the meetings.

I also express my gratitude to A.J. Zondervan of Alliander as the external supervisor, for taking me to all sorts of meetings, advising me on the people to interview, showing me around at Alliander and, most of all, for the weekly feedback and active involvement in the project. I would also like to thank M. Danes, who although was not officially in my committee, I do consider my 6th supervisor. Thank you for your enthusiasm for my project for all your feedback. Thanks Alliander for providing me with this opportunity. From the beginning I've felt that my project was really a project for Alliander, which will be of use after my internship. I could make it my own project, while still being part of a team.

I especially want to thank two people: Amber and Laurens. The hours we've spend together were of great help during the whole project, and especially during the later stages. I truly enjoyed our hours spend together in the project room, our many walks and dinners in the Hangout. Without their help, this thesis would not be what it is now. I would also like to thank my girlfriend Anke, for letting me basically use her house as a hotel for a number of days almost every week, and for understanding my absence in the last months of the thesis. Lastly, I want to thank my parents and brother, Martijn, for all their support during this thesis and my entire study.

Delft, 2017,

Ron Pieter Swart

Summary

Research problem

The government of the Netherlands aims to make the CO_2 emissions of all low temperature heating of houses, buildings and greenhouses neutral in 2050 in line with the Paris Agreement. Currently, over 90% of low temperature heating systems are dependent on fossil gas for heating and cooking. Therefore, the gas boilers need to be substituted within 33 years, which is a complex task. Possible options are heat grids (fed from residual and geothermal heat), electric heat (heat pumps) and biogas, while lowering the energy demand through insulation measures.

Heat pumps (HPs) are seen as one of the technologies to fill a part of the gap left by gas. Heat pumps however, use electricity, which increases the flow on the electricity grid, while gas flows decrease. For DSO as Alliander it becomes harder to predict what the required investments in the distribution grid are. Analysing the diffusion of heat pumps in the Netherlands can thus help DSOs to manage their assets. One of the biggest barriers for heat pumps are the costs. Before a household can install a heat pump, it requires a house with proper insulation and a low temperature heating system, which is not present in the majority of houses. This means that households should be stimulated by policy measures in order for them to switch, which is why the following research question if formulated:

What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using Agent Based Modelling?

This research is further scoped towards existing households, within the Liander area and excluding newly build houses. Three types of heat pumps were taken into account: Hybrid Heat Pumps (HHPs), Air Sourced Heat Pumps (ASHPs) and Ground Sourced Heat Pumps (GSHPs). A HHP is a combination of a small gas boiler and an ASHP.

Methodology and the main elements of the model

The research question is answered by using Agent Based Modelling (ABM). ABM enables modelling diffusion of innovation and adoption dynamics, since that is an area where typically emergent phenomena arise, one of the key elements of ABM. It has been widely used for innovation diffusion studies. It takes into account the soft factors of adoption and the heterogeneity of a population, which makes it possible to model human behaviour. The psychological model used as a basis for the ABM is the Theory of Planned Behaviour (TPB). In the theory three attributes determine the intention towards a behaviour: the attitude, subjective

norms and the perceived behavioural control (PBC). The Attitude concerns the perceived consequences that result from the behaviour, Social Norms cover morals from the environment and the Perceived Behavioural Control is about the perceived ease or difficulty of performing the behaviour. The TPB was merged with the following 8 factors to form the basis of the model:

1. Savings: the expenditures that a household would have if it would keep using a gas boiler subtracted by the expenditures of a situation with a heat pump instead
2. Energy-label stimulation: Stems from a hypothetical situation where the government puts pressure on households to improve their energy-label
3. Social influence: originates from the social network of the households. The more peers adopt heat pumps, the higher this factor will be
4. Investment costs: a factor representing the perceived value of the total upfront investment costs to be fulfilled by a household.
5. Payback time: The number of years it takes before the household's total investment for the heat pump is payed back. Dependent on the savings and investment costs
6. Income factor: Represents the income level of a household
7. Environmental benefit: A factor that represents the amount of reduced CO2 emissions when a heat pump is adopted compared to the old situation with a gas boiler.
8. Hassle factor: The inconvenience the implementation a heat pump brings.

Before the households evaluate these factors, first they have to meet the following conditional checks: (1) they should have a reason to consider heat pumps, which represents the failure the existing heating system and (2) they should be aware of the existence of heat pumps and (3) they should have sufficient resources, in the form of a suitable house and budget.

The Results of the ABM

The financial incentives were evaluated using multiple experiments. The individual influence of the incentives was tested, as well as a scenario analysis with multiple incentives. Some further exploration was done into temporary incentives. All results discussed below are within the model scope, assumption and limitations in this thesis.

It can be concluded that the model follows a similar pattern to that of Rogers's diffusion of innovation theory. Subsequently, the influence of the four parameters was analysed. Based on these results, none of the parameters had a significant effect on the general pattern of adoption. Under all parameter settings, the emergent behaviour of the model was an S-shaped pattern. Of the four parameters, subsidies and the gas price growth per year have the largest influence on the adoption rate. The possibility of the leasing has little influence on the overall adoption, because it only improves the investment factor for some households, and within that factor, the influence is not crucial.

The scenario analysis consisted of only the gas price and the subsidy. In total, five scenarios were developed, as is shown in Figure 1. The emergent pattern of most of the scenarios is similar to that of the base scenario. The *Customer Choice* scenario however shows an almost linear growth until 2050. The *Electrification* scenario shows an total adoption of heat pumps of around 80% in 2050. In this scenario, the subsidy and gas price increase are both very high. Also it is concluded that high subsidy levels (80-100%) causes higher heat pump adoption compared to high gas price growths (4-5% per year).

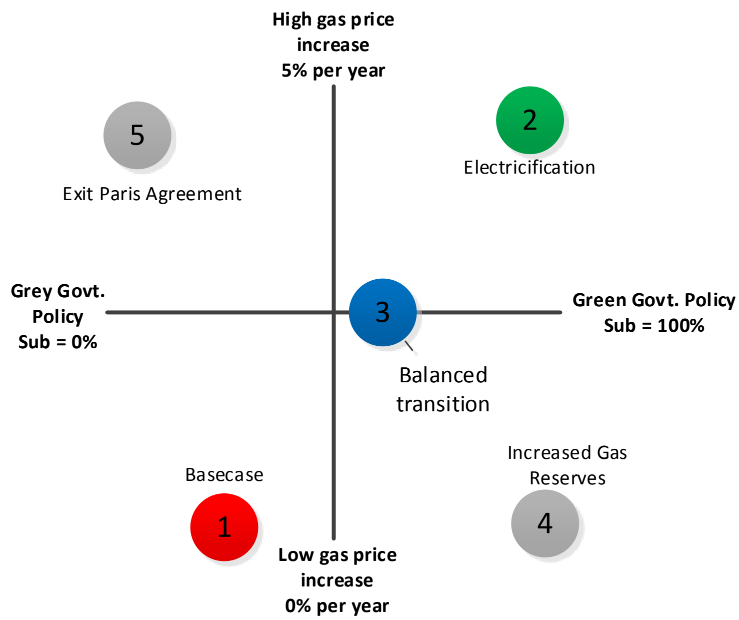


Figure 1: The scenario space of the financial incentives for subsidy and the gas price

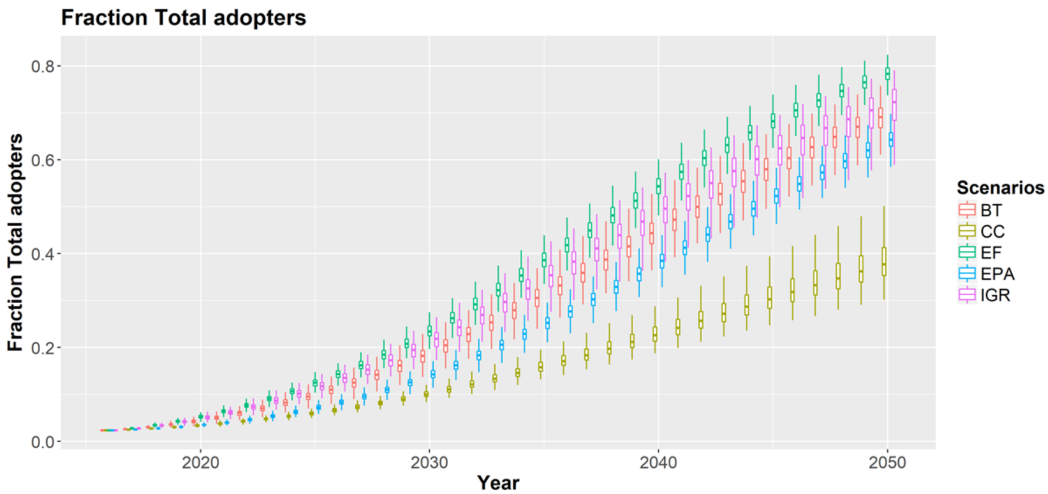


Figure 2: The cumulative total adopters over time for the five scenarios. The sequence of the boxes is according to the scenarios in the legend on the right. BT = Balanced transition, CC = Customer Choice, EF = Electrification, EPA = Exit Paris Agreement and IGR = Increased Gas Reserves.

Further exploration of the model was done by changing the duration of the financial incentives. Instead of a fixed measure over the complete time-frame, a short spike of subsidy or gas price was set up. A short spike in subsidy or gas prices changed the emergent pattern of adoption slightly, as the adopters per year were much higher for the duration of the incentive. Another experiment was executed where a temporary high subsidy goes along with higher awareness levels and a higher chance on reason for all households. This lead to drastic changes in model behaviour. The adoption skyrockets in the years of the incentives.

Conclusion and discussion

The influence of the financial incentives can be split in two. There is the energy label requirement and leasing which have relatively little effect and on the other side the gas price growth and subsidy, greatly altering the adoption of heat pumps. The economic aspects, payback time, savings and the investment costs are the reason for these differences. This economic barrier proves also to be the determining factor for adoption in this thesis. Leasing constructions for just the heat pumps will not help much according to this model. Only when the total investment is lowered by leasing, thus also LTH and insulation, leasing will be an effective tool for stimulating heat pump adoption. A high gas price growth, surprisingly also stimulates hybrid heat pump adoption just as much as ASHPs and GSHPs, even though the HHPs still use gas. The little amount of gas still being used is thus of much influence on the total variable costs.

When looking at specific groups and their adoption behaviour, then the middle incomes are most affected by subsidies and leasing (that is leasing for the HP, insulation and LTH). As for the household groups, generally the groups with the lowest average incomes, the unaware energy users and faithful environmentalist, are most affected.

The best option for heat pump adoption might be to look into raising awareness of households. An experiment where the subsidy affected the awareness and reason of households, shows a drastic increase in adoption. It must be noted that the relation between subsidy vs awareness and reason was not implemented based on extensive research, but rather to explore the effect.

Discussion

The results show that the results of the models experiment is an S-curve, similar to Rogers DoI and mathematical models such as Fisher and Pry. Mathematical approaches are not ideal for innovation diffusion studies, as they generally lack the possibility for communication between agents, lack heterogeneity, do not take into account micro-level factors of adoption and cannot accurately describe how households with different preferences make decisions. In the model these aspects are taken into account, yet the results are similar. This might indicate that the decision making process is modelled rather simple and households make rather rational decisions. The variance of the results also indicates that the model is fairly deterministic. Also the interaction between the agents in the model is minimal. The social influence does involve some interaction, however, this factor has a limited effect on the model results.

The question thus arises whether this model is of added value compared to Fisher and Pry and the Bass model. Shouldn't a mathematical model be used instead of this ABM if the results are similar? For the main version of the model, the answer is yes. The four incentives in this model could be altered and set for the entire period results in diffusion curves that are likely to be reproduced by mathematical models such as Fisher and Pry or the Bass model. However, when the financial incentives become dynamic over time the model provides an edge over the mathematical models. This effect was visible for a temporary high subsidy and gas price for 1 to 5 years, as well as for a static and adaptive subsidy budget. The real added value of the model is provided by the experiments where the awareness and reason are altered. Here the model shows behaviour which is not possible with conventional mathematical models, or at least under the basic conditions of the Bass model. This does not imply that these results are realistic however, as the oscillation in the model is probably not a realistic consequence of such a measure. It must also be noted that the implementation of the dynamic incentives is suitable for more research, as the implementation was done rather quickly.

Many assumptions had to be made for the model, which means the model is bound to some limitations. An important one is the lease-or-buy decision. The formalization of this decision is simplistic and does not include all elements of a leasing contract. The psychological aspect of leasing is not included. Whether the implementation of the lease-or-buy decision is sophisticated is thus questionable. Also, due to a lack of empirical data, assumptions had to be made concerning the preferences of households. A study into the these preferences would give more insight in the different preferences per household group.

Table of contents

List of figures

List of Tables

List of abbreviations

TPB	=	Theory of Planned Behaviour
PBC	=	Perceived Behavioural Control
GSHP	=	Ground Source Heat Pump
ASHP	=	Air Source Heat Pump
HP	=	Heat Pump
HHP	=	Hybrid Heat Pump
DSO	=	Distribution Systems Operator
ABM	=	Agent Based Modelling
HVAC	=	Heating, Ventilation and Air Conditioning
PV	=	Solar Photovoltaics
EV	=	Electric Vehicles
E-label	=	Energy-label
SN	=	Social Norm

Part I

Chapter 1: Introduction

Chapter 2: Innovation diffusion and Agent Based Modelling

Chapter 3: Factors influencing heat pump adoption

1

Introduction

1.1 Background

Following the Paris Agreement late 2015, the Ministry of Economic Affairs of the Netherlands published a new energy policy report, The Energie Agenda 2016 (Ministry of Economic Affairs, 2016a), with its main plans how to make the country CO_2 neutral. Low temperature heating of houses, buildings and greenhouses is one of the central pillars of the report. This is not surprising, as currently around 90% of households, buildings and greenhouses in the Netherlands are dependent on fossil gas for heating and cooking (Ministry of Economic Affairs, 2016a). Other technologies therefore are needed to ensure that the government's goals are achieved and buildings remain heated. Possible options presented in the *Energie Agenda 2016* are heat grids (fed from residual and geothermal heat), electric heat (heat pumps) and biogas. Lowering the energy demand through isolating houses more properly is also one of the measures used in reaching the goals of the Ministry.

It is very unlikely that single technology will be as dominant as gas boilers are now. A heat grid is one of the options, especially in places with a high population density. They have the potential to supply half of the heat demand of the Netherlands (PBL, 2017). Heat from deep geothermal sources, and residual heat from industry can be transported directly to the customer. Biogas is a very attractive option to replace natural gas, because the current gas infrastructure can be used and current gas boilers and radiators can be used. However, the low availability and high prices are problems, which is why it will only develop locally on a small scale (CE Delft, 2015). Electric heating can be either with heat pumps or resistor heating. Heat pumps are the most efficient form of electric heating (Mustafa Omer, 2008). Heat pumps are most cost-effective in the rural areas, where distances are too large for heat grids to be viable. Many studies conclude that heat pumps have a great potential for the future (CE Delft, 2015; DELTA, 2012; Dutch Heat Pump Association, 2013; ECN, 2016b). In the remainder the of the research, the focus will be on heat pumps.

In the Energie Agenda 2016, heat pumps (HPs) are seen as one of the technologies to fill a part of the gap left by gas. At the same time, the amount of solar panels and electric vehicles increases. All three result in more energy flows on the electricity grid, energy flows that are also harder to predict, especially with the intermittent nature of solar power. This leads to an increase in electricity usage of households in the coming decades, and a more difficult task for a DSO as Alliander to predict what the required investments in the distribution grid are (van Zoest, Veldman, Lukszo, & Herder, 2014). It is not surprising that Alliander see this as one of their main challenges for the future (Alliander, 2015).

1.2 Heat pump technology, the scope, potential and financial incentives

1.2.1 Heat pump technology and barriers

HPs function as follows: thermal energy from the air, water or ground, is used by the heat pump to convert it into useful heat. Generally, HPs can be divided into ground source heat pumps (GSHP), Air Source Heat Pumps (ASHP) and hybrid heat pumps (HHPs). GSHPs use ground water, surface water or the soil as a heat carrier. Logically, ASHP uses the air. A HHP can be a combination of multiple options. In the Netherlands, this is generally a combination of a gas boiler and an ASHP. HHPs are an attractive option for households and project developers in countries with a comprehensive gas infrastructure such as the Netherlands.

Of the different HP types, especially the GSHP has the potential to become a popular climate control system, as they can provide one of the most energy efficient ways of heating and cooling buildings (Mustafa Omer, 2008). The main logic behind this is because due to the high thermal inertia of the soil, the ground temperature below a certain depth remains reasonably constant (Florides & Kalogirou, 2007). Furthermore, GSHPs outperforms both ASHPs (including HHPs) and conventional heating systems (electric heaters based on oil, diesel or coal) on many aspects: lower maintenance, energy and life cycle costs, less required refrigerant, simpler designs, low noise, no local pollution, a higher efficiency and generally higher CO_2 savings because of the higher Coefficient Of Performance (COP) (Blum, Campillo, & Kölbel, 2011). Nonetheless, like most promising technologies, a GSHP has implementation barriers. A major one is the high capital investments needed for drilling and installation (Blum et al., 2011). A GSHP alone costs between 10 and 20 thousand euros, where insulation is around 12 thousand euros on average (B.4 & 0) Additionally, low acceptance and awareness levels of the public are problematic (Chua, Chou, & Yang, 2017; Mustafa Omer, 2008). As of 2017, the amount of total installed heat pumps is still low, and heat pumps bring a lot of hassle for a household.

These barriers are also true for ASHP, albeit to a lesser extent. Because there is no drilling needed for ASHPs and hybrid HPs, the costs are considerably lower (Warmtepompinfo.nl, n.d.). Furthermore, because these HPs are generally easier to install, the acceptance is also likely to be higher. So even though the GSHP is the better option on the long-term, many households and project developers choose an ASHP. In 2016, the total number ASHPs and GSHPs installed were around 140.000 and over 40.000, respectively (CBS, 2017c)

The COP is an important aspect of heat pumps. It is defined as the ratio between the useful produced thermal energy, and the energy consumed to obtain it, called the drive energy (Sarbu & Sebarchievici, 2014). Heat pump systems are powered by electricity; thus the drive energy is electricity. The performance of the system depends on both the input and output temperature, but also on the heat pump system itself. Because the soil is generally warmer than the air, the COP of GSHP is larger. On average, the COP of GSHP systems is 4, which is very high compared to a COP of 1 of electric resistance heating (Mustafa Omer, 2008). For ASHP systems the COP is considerably lower, with a value around 2-3 (Brown & Stebnicki, 2011).

1.2.2 Scope

As the complete system is very complex, it is necessary to work within a certain scope. The focus here will be on residential owned houses and not rentals. It is chosen to focus solely on owner-occupied houses because its residents can make their own decisions. Also, the focus in this thesis is on the decisions by individual households, and tenants do generally not make individual investment decisions concerning their heating system. Also, owners are more likely to invest than tenants (Heiskanen & Matschoss, 2016). In the market potential, it was stated that heat pumps will have a better business case in rural areas, and that urban areas will be likely supplied through heat grids or biogas. Although it would be interesting to model different parts of the Netherlands, and to include the geographical aspects, the focus in this thesis is to analyse the general behaviour concerning heat pump adoption.

District heating, biogas and other technologies will not be taken into account. Also not all types of heat pumps will be used, as there are too many. Generally, heat pumps are either air sourced or ground sourced. Within ASHP, a distinction is made between pure ASHP and hybrid heat pumps. With the latter, an ASHP unit is combined with a gas boiler. Although technically ASHP and GSHP are also hybrids, as they generally use a small electrical back-up heater, they are not considered as hybrids. For the rest of this thesis, with hybrid is meant, a heat pump with an ASHP unit and a gas-boiler. A more comprehensive description is provided in 3.3.

The region used for the study is the Liander region in the Netherlands (see Appendix A:). This comprises over 1.6 million owned houses. Although a region is chosen, this does not mean that geographical spread will be analysed, as the first goal for Alliander is to gain insight in the general adoption over their complete region. A representative sample of households will be used for the Liander region.

1.2.3 Market potential

In order to get a feeling on the potential of heat pumps in the Netherlands, it is useful to look at research done into this topic. The results from different reports in the last 5 years are given below in chronological order.

As of 2016, the total residential heat pumps installed in the Netherlands is around 180,000, of which almost 80 percent are ASHPs (CBS, 2017c). As can be seen in Figure 3, the amount of installed ASHPs increases drastically compared to GSHPs from 2010 and on. This is explained by the introduction of the subsidies and the fact that ASHPs are generally cheaper than GSHP, and therefore is an attractive option. Possibly, the increased popularity of hybrid heat pumps is also a factor here. When looking at the cumulative installed capacity in Figure 4, one can clearly see that the GSHP installations have a large capacity, as for a long period their total installed power was higher than ASHP, despite having much lower number installed in total.

In the UK, DELTA (DELTA, 2012) laid out pathways for domestic heat, specifically for the UK. It was aimed to study the optimal appliance technology pathways for heating technologies, their impact on consumers, and on the gas and electricity grid. Three pathways were constructed and analysed:

1. *Customer choice*: Customers choose their heating systems. Gas remains dominant this pathway with only 1% uptake for HP retrofit. Emission targets will not be reached.
2. *Electrification*: large scale electrification to reach zero carbon. Results in 46% uptake for HP retrofit, but households have to pay higher upfront costs and operational costs compared to gas-boilers. This is a costly scenario, but more stringent emission targets will be reached.

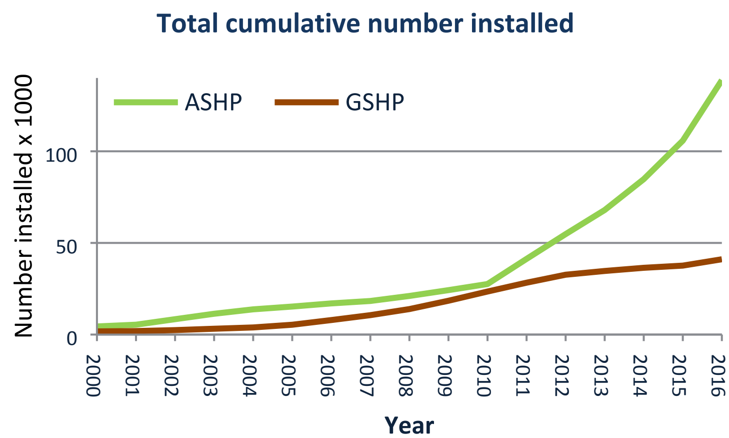


Figure 3: Total cumulative number installed heat pumps in the Netherlands from 2000-2016 (CBS, 2017d)

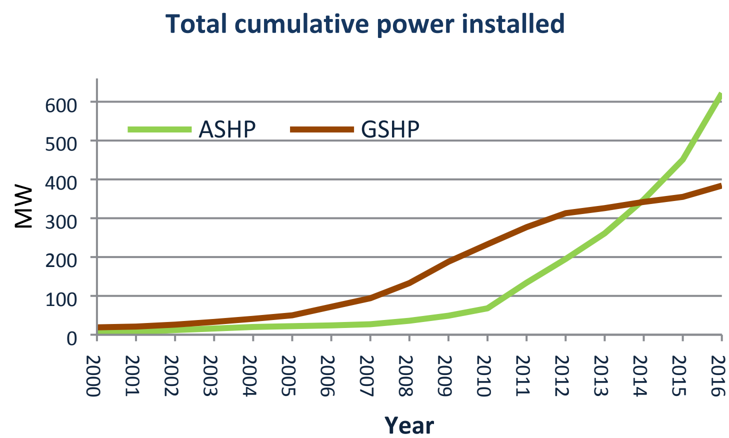


Figure 4: Total cumulative installed power from 2000-2016 in the Netherlands (CBS, 2017d)

1. *Balanced transition:* A pathway with a mix of heating technologies including gas. There is a less aggressive heat pump adoption than pathway 2. The *Balanced Transition* pathway results in 24% uptake of electric HP in 2050. This pathway is not as costly as pathway 2, yet there are still considerable lower CO_2 emissions in the domestic heating sector.

Four types of heat pumps are taken into account in all pathways: ASHP, GSHP, hybrid heat pumps and gas heat pumps, of which ASHP and GSHP are stated to be relatively mature technologies. HP uptake is highly dependent on the retrofit in existing buildings, the rate of electrification and the electricity price. Customer wise there is very little understanding of HP technology and between heating players the views are very different on heat pump potential. There are groups that think heat pumps are only suitable for very well insulated homes with low thermal heat demands. Others think heat pumps can be applied everywhere as long as they are sized correctly. The latter is the view by DELTA.

The Dutch Heat Pump Association (DHPA) presented a positioning paper for heat pumps in 2013 (Dutch Heat Pump Association, 2013). Based on the estimates by the *Planbureau voor de leefomgeving*[1] and ECN[2] the DHPA takes 500.000 heat pumps installed in the residential sector in 2020 as a target. Looking at the growth from 2015 to 2017 of around 90.000 heat pumps and the total in 2015 of 143.000 (CBS, 2017c) this might be too optimistic. The DHPA foresees a big role for hybrid heat pumps. Furthermore, they propose a lower energy tax for HP owners, lower VAT for HPs and other tax advantages. Most potential can be found in the detached and semi-detached houses.

Another indication of the potential of heat pumps in the coming decades comes from CE Delft (CE Delft, 2015). Commissioned by GasTerra, the main gas supplier in the Netherlands, they provided an overview of the future heating system of the build environment, under the assumption that the sector is completely emission free in 2050. The estimations are purely based on economics. Per neighbourhood type, the cheapest option is assumed to be the best. Possible options are biogas, residual heat, geothermal heat, heat pumps, resistance heating, seasonal thermal energy storage, and biomass. Their conclusion is that the cheapest option is different for each neighbourhood type. Heat pumps have potential in all neighbourhood types, especially in areas with a lower building density. Furthermore, the higher the biogas price, the more dominant all electric energy systems (and thus heat pumps) become. Based on the costs, CE Delft thus concludes that heat pumps will become a mainstream technology towards 2050.

A group of Dutch organizations (ECN, PBL, and CBS & RVO) presents the yearly developments in the energy sector in the Netherlands called the *Nationale Energieverkenning* (ECN, 2016b). They estimate that heat pumps take up 5% in 2020 and 10% in 2030 of the heating systems (ECN, 2016b)

Logically, DSOs such as Alliander also put effort in developing scenarios and analyses for heat pump adoption. Commissioned by Alliander, the model behind the CE Delft study, CEGOIA, is applied by CE Delft to the Liander region, which concerns around 2.5 million houses. Based on the information if heat pumps where the most cost-effective option for a neighbourhood, a diffusion model was made (internal report at Liander). This resulted in a more even spread of heat pumps over the Liander region, with the number of heat pumps being estimated to be

[1] The *Planbureau voor de leefomgeving (PBL)* is the National institute for strategic policy analyses considering environment, nature and spatial development.
[2] Biggest Dutch research institute on energy

around 1.1 million in 2050 for owner-occupied houses and private rental houses. In another analysis Alliander developed three scenarios which they think seemed likely, scaled on the axis whether electric is dominant or gas. These scenarios are similar to the ones mentioned in the report by DELTA (DELTA, 2012). The scenarios are:

1. *Electrification*; renovations and new houses are equipped with HPs and insulation on a large scale. Leads to a HP penetration of 69% HPs in 2050.
2. *Phased electrification*; until 2030 the focus is mainly on insulation, and after 2030 on HPs when the costs have decreased. Leads to a penetration of 50% HPs in 2050.
3. *Insulation*; Focus is mainly on insulation, low amount of HPs. Leads to a penetration of 18% HPs.

Furthermore, it is stated that in 2030 there is a relatively low level of heat pump penetration, somewhere between 4 and 20%, which is similar to statements made by DELTA (DELTA, 2012), and that the shift to low temperature heating will go slowly because of the significant societal costs involved.

Commissioned by Alliander, BCG analysed scenarios for gas grid defection, and they estimate that in 2050 only 12% of the current gas usage can be provided in a sustainable way in the Netherlands. They state that under current conditions (business case, regulation), the adoption of heat pumps will be around 6 percent, as adoption only takes place at houses with proper insulation and house owners with a clear environmental concern. Even though BCG assumes that the business case of heat pumps will improve, the dependence on gas will remain high as insulation costs take up more than 50% of the total investment for an electric heat pump. In the energy neutral 2050 scenario, where it is assumed that stimulating measures by the government have taken place, the amount of gas connections decreases with 91%, with the remaining connections being supplied by biogas. More than half of the households in the Liander region will have adopted a heat pump.

Many institutions thus expect heat pumps to take up a more dominant role in the future. In some scenarios, such as the Customer Choice scenario of (DELTA, 2012), the adoption is rather low with 1%. In other scenarios, the uptake is much higher. Especially in areas with a lower density, heat pumps are expected to be the most cost-effective option.

1.2.4 Financial incentives

Heat pumps thus could potentially dominate the future of the residential heating market. However, as mentioned earlier, the biggest barrier to heat pump adoption are the high capital costs. Therefore it is likely that households need some stimulating measures to steer them towards heat pumps. These measures will henceforth be named the financial incentives. A well-known financial incentive is subsidy, which are already in place in the Netherlands under the name of ISDE[3]. The energy prices also largely determine the financial business case. As heat pumps have to replace gas boilers, the gas price could also make a difference. Heat pumps themselves use electricity, thus the electricity price is also relevant. Government policy and the financial incentives are thus a major factor in heat pump diffusion.

1.3 Why is research needed?

As stated in the introduction, the switch from fossil gas to other heating technologies poses questions. Heat pumps concern one of the technologies that is likely to gain momentum, albeit under the conditions that the business case improves, and the government puts stimulating measures in place. The reports cited in the market potential in 1.2.3 are mainly based on economic parameters, leaving out social aspects. These reports give an indication, but that could be improved by taking into account human behaviour. In the end, it is the household that makes a decision whether to adopt or not. Therefore, there still are a lot of uncertainties considering heat pump diffusion.

For the DSOs gaining insight in diffusion is important, as they have to decide whether their electricity network assets need to be strengthened, since HPs use electricity as the driving source. In the previous paragraphs the following becomes clear. Firstly, heat pumps are one of the technologies for which the government foresees a significant role in the future in the transition from a gas to other heating systems. Secondly, many institutes conclude from their reports in 1.2.3 that the number of heat pumps will increase significantly. The numbers however have a wide range of results, and are under all sorts of different assumptions and scenarios. The aim of this thesis is to provide more insight into the workings of heat pump diffusion in the Netherlands. It will be difficult to provide information concerning exact numbers of the adoption rate, but insight can be provided about the influence of certain measures. Also information about the adoption per subclasses of households. Opposed to the estimations in the previous paragraph that are mostly based on the business case, this thesis also takes into account the adoption behaviour of households. As the aim is to analyse the adoption of households, the focus in this thesis is solely on owned residential houses.

Agent Based Modelling enables modelling diffusion of innovation and adoption dynamics, since that is an area where typically emergent phenomena arise, one of the key elements of ABM (Bonabeau, 2002). In the past years, ABM has been widely used to simulate adoption and

[3] InvesteringsSubsidie Duurzame Energie, which translates to investment subsidy for renewable energy

diffusion processes (Kiesling, Günther, Stummer, & Wakolbinger, 2011; Palmer, Sorda, & Madlener, 2015). For instance with greenhouse agriculture (Schreinemachers, Berger, Sirijinda, & Praneetvatakul, 2009), environmental innovations (Palmer et al., 2015; Schwarz & Ernst, 2009; Sopha & Klöckner, 2011) and alternative fuel vehicles (Ting Zhang, Gensler, & Garcia, 2011). As such ABM will be the used method for this study.

In *table 1* below, an overview is given of current literature. Studies have been done on the adoption of heat pumps using ABM (Snape, Boait, & Rylatt, 2015), case studies (Burley & Pan, 2017) and stochastic simulation (Hlavinka, Mjelde, Dharmasena, & Holland, 2016). Overall, the topic of innovation diffusion with different technologies has been studied extensively, with ABM and other methods, as can be seen in Table 1. Furthermore, ABM has been used for modelling energy related problems in multiple sources. Innovation diffusion in the Netherlands has been studied as well; however heat pumps have not been the subject of such studies. Lastly, numerous studies have been performed about the factors influencing microgeneration or innovation adoption. The study that suits the description presented here is by Snape et al. (2015). However, this study was performed in the UK and focused on a rural area, off the gas-grid, favourable for the feed-in tariff of the UK. A relatively small region has been analysed. Another point of difference with current research is the timeframe. Snape et al. (2015) modelled for three years, which is significantly shorter than the period from 2017 to the target year of the government, 2050. The focus there is thus on the relative short term. Long term diffusion studies considering heat pumps have not been performed yet. Furthermore, in the Netherlands, it is aimed that all households switch before 2050, therefore households should switch whether they are on or off the grid. Furthermore, virtually every household is connected to the gas infrastructure in the Netherlands. Hence all (owned) households will be taken into account that are connected to the gas infrastructure. It is likely that households connected to the grid have another perception about heat pumps than the ones not connected to the gas grid. The social factors in the study by Snape et al. (2015) comprise the neighbourhood factor and appropriateness.

An ABM model of heat pump diffusion in the Netherlands does not only fill a gap in the literature, it is also useful for multiple organizations. For the DSOs this diffusion is important, as they have to decide whether their electricity network assets need to be strengthened, since HPs use electricity. Furthermore, they make long-term investments (e.g. 40 years) in the grid. Therefore, future diffusion of heat pumps is already relevant for current investment decisions at the DSO. Currently, Alliander has a model, called ANDES, in which diffusion curves functions as an input. The ANDES model gives insight about the status of the assets in the coming decades. The diffusion curves used now are based on an equation by (Fisher, 1971), which is made topdown, and fitted towards an S-curve. This means that all households are seen as homogeneous, whereas in reality they make different choices.

Table 1: Literature overview on innovation diffusion.

Topic	Articles
Heat pump diffusion studies using ABM	(Snape et al., 2015)
Heat pump diffusion studies with a case study[1] and a combination of forecasting and stochastic simulation[2]	(Burley & Pan[1], 2017; Hlavinka et al[2]., 2016)
Heating systems diffusion using ABM	(Sopha, Klöckner, & Hertwich, 2013)
Heating systems diffusion with empirical modelling[3] and Structural Equation modelling[4]	(Bjørnstad[3], 2012; Sopha & Klöckner[4], 2011)
Studies using ABM for modelling the energy sector	(Chappin & Dijkema, 2017; Vasiljevska, Douw, Mengolini, & Nikolic, 2017; Veselka, Boyd, Conzelmann, & Koritarov, 2001)
Studies analysing the diffusion of innovations using ABM	(Palmer et al., 2015; Rai & Robinson, 2015; Schwarz & Ernst, 2009; Ting Zhang et al., 2011)
Studies about innovation diffusion in the Netherlands	(M. van Dam, 2016; Dieperink, Brand, & Vermeulen, 2004; Houwing & Bouwmans, 2006; Van der Veen & Kasmire, 2015)
Studies concerning factors influencing microgeneration or innovation diffusion	(Balcombe, Rigby, & Azapagic, 2013; Leenheer, De Nooij, & Sheikh, 2011; Michelsen & Madlener, 2016)

The usefulness of a heat pump diffusion model for policy makers becomes clear when looking at largest barrier for microgeneration adoption, the costs (Balcombe et al., 2013). A GSHP alone costs around 15.000 euros, however for existing residential houses in scope here, the investments are even higher. In many cases the needed investment in insulation is equally high as the heat pump investment itself. Adding the needed replacement in heating delivery systems the total investment cost is significant. Therefore, it can be assumed that many households don’t have the resources to do such an investment. Policy measures by the government are thus essential to stimulate heat pump adoption. Besides price based measures such as subsidies, policy makers might want to test other types of measures. This could also be made possible with resulting model of this thesis. Apart from subsidies, market developments can also be tested. Instead of simply buying a heat pump, a household could lease or rent one. Lending out devices is an effective measure for increasing the diffusion of feedback devices (Jensen, 2017). The investment decision can be influenced by a number of organizations, such as energy companies, banks or DSOs like Liander (Heiskanen & Matschoss, 2016).

1.4 Research questions

The research question is as follows:

What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using ABM?

With the corresponding sub questions:

1. What is a suitable diffusion theory to function as a basis of the model?
2. What factors are identified in the literature to influence diffusion of HPs and should therefore be included in the model?
3. How do the factors of question 2 fit within the diffusion theory of question 1 to form an ABM and how should the overall ABM look like?
4. What insight can be gained from the results of the experiments of financial incentives?

1.5 Structure of the thesis

The research is structured as visualized in Figure 5 and is separated into four parts. The first part concerns desk research and expert interviews to select possible theories and get an overview of all the factors that are relevant in the choices of a household in their choice for a heat pump.. Part II is a guide to arrive from the system description to the model implementation. Part III concerns the outcome of the model, such as experiments, results and validation. Part II and part III are steps that are all based on the book *Complex Adaptive Systems* by (K. H. van Dam, Nikolic, & Lukszo, 2013). The thesis is concluded in part IV, where the central research question is answered.

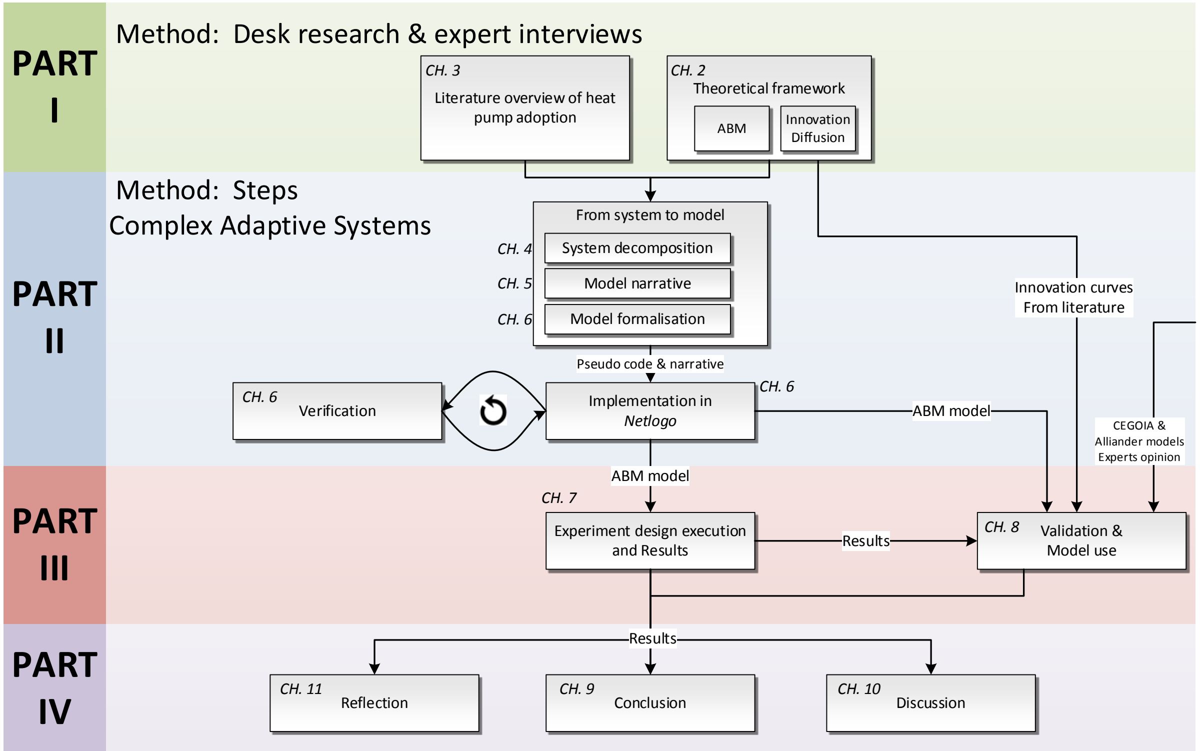


Figure 5: Structure of the research. Parts II and III are based on (K. H. van Dam et al., 2013)

2

Innovation diffusion and Agent Based Modelling theory

Now that the research question is clear, we move on to answering the first sub question. Here the first sub question will be answered:

Sub question 1: *What is a suitable diffusion theory to function as a basis of the model?*

Literature considering innovation diffusion theory will be assessed and compared. Both mathematical and psychological models will be handled. At the end, a choice is made considering the most suitable theory on which the model will be build. Before the innovation literature, a brief overview of agent based modelling is presented in 2.1. A short conclusion will follow where the sub question will be answered.

2.1 Complex adaptive systems and ABM

2.1.1 Complex Adaptive Systems

In order for a system to be modelled using ABM, the system should fit the characteristics of a Complex Adaptive System (CAS). The following definition by Waldorp (1992) will be used:

> "A complex adaptive system is a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a complex adaptive system tends to be highly dispersed and decentralized. If there is to be any coherent behaviour in the system, it has to arise from competition and cooperation among the agents themselves. The overall behaviour of the system is the result of a huge number of decisions made every moment by many individual agents."

Heat pumps and other heating systems are part of the gas and electricity energy infrastructure. These infrastructures have been perceived as complex adaptive socio-technical systems (Scholten et al., 2016). Heating systems such as gas boilers, heat pumps, and heat grids are all connected to energy infrastructures. Some to the gas grid, some to the electricity grid, where heat grids are grids on their own and some are connected to all grids. The energy infrastructure systems are complex systems, because of the many interacting social and physical components (Chappin & Dijkema, 2017)

2.1.2 Agent Based Modelling

Heat pump diffusion comprises a lot of factors that are of influence. One of the most important factors concerns the costs of heat pumps, resulting in a payback period. Furthermore, households are different. Firstly, their demographics are different throughout the Liander region. Second, the type of region is important, which is about urban and rural regions and everything in between. The Liander region can be divided into sub-regions, according to postal code levels, where postal code level 4 (e.g. 2628) is the highest level, and postal code 6 (2628BX) the most detailed. ABM is especially useful when a population is heterogeneous and the spatial element is important (Bonabeau, 2002). The latter is represented by the neighbourhood effect (also known as contagion factor). The neighbourhood effect has a big influence on the diffusion of a microgeneration technology, as is stated by (Noonan, Chiang Hsieh, Matisoff, Hsieh, & Matisoff (2013) by analysing the effect with Heating, Ventilation and Air Conditioning (HVAC). This means that households are more likely to choose for an innovation when members of a household's social network have already done this. Furthermore, current reports described in paragraph 1.2.3, heavily focus on the business case of heat pumps, but leave out social factors that also influence decisions of households. Another example is the relation between suppliers and households. Currently the majority of suppliers focuses on installing gas boilers and just started paying attention to heat pumps. Because of this, the chance that households choose a heat pump is lower. On the other hand, when suppliers are pro-heat pumps (i.e. heat pumps are profitable), the acceptance and attitude of households is likely to be more positive to HP.

Another reason why ABM is useful in these situations is because diffusion of innovation and adoption dynamics is an area where typically emergent phenomena arise, which are one of the key elements of ABM (Bonabeau, 2002). Examples of where diffusion is modelled with ABM are with greenhouse agriculture, environmental innovations and alternative fuel vehicles (Schreinemachers et al., 2009; Schwarz & Ernst, 2009; Ting Zhang et al., 2011). Specifically for the diffusion of heat pumps, one previous study has been performed, by Snape et al. (2015) for modelling heat pump adoption in the UK and analysed non-financial barriers using ABM. That article modelled a small region of around 4,000 households. This choice of aggregation is a good starting point for this study, especially when taking into account the neighborhood effect. In the proposed model the Liander region will be scaled down to a fictitious but representative population. In the Liander region there are 145.000 postal code 6 regions with an average of 16 households. This could be scaled down to 145 postal code 6 regions. The division of neighborhood (urban, semi-urban, rural etc.) types in the Liander region will be represented. This way individual households can be modelled, instead of aggregated house blocks. To get the right level of detail is important, but also difficult, as can be seen in the first disadvantage in *table 2.*

ABMs are build bottom-up in order to investigate emergent behaviour (K. H. van Dam et al., 2013), and typically have three elements: (i) agents, their attributes and behaviours, (ii) agent relationships and methods of interaction and (iii) Agents' environment, in which the agents live (Macal & North, 2014). Bonabeau (2002) provides a clear overview of the advantages and disadvantages of ABM, as is summarized *table* 2. The disadvantages described in Table 2 show some pitfalls. When going into much detail, it can become very complicated, and it also can take a lot of computational power. Therefore, when using ABM, one is bounded by the level of detail. On the other hand the model should be of sufficient detail, else it is not possible to capture the complexity of the system. Another challenge lies in the fact that heat pump diffusion is dependent on soft factors, however, as Bonabeau (2002) states, ABM is the only modelling technique capable of modelling such situations.

Table 2: Advantages and disadvantages of ABM (Bonabeau, 2002)

Advantages	Disadvantages
ABM captures emergent phenomena, which result from the interactions of individual entities.	'The model has to be built at the right level of description, with just the right amount of detail to serve its purpose; this remains an art more than a science' (p. 7287)
ABM provides a natural description of a system. 'In many cases, ABM is most natural for describing and simulating a system composed of ''behavioural'' entities' (p. 7281)	Human behaviour comprises soft factors (irrational behaviour, subjective choices etc.), can be very difficult to capture, although ABM is the only modelling language to deal with such situations.
ABM is flexible as agents can be added easily and complexity of the model can be tuned.	Modelling at a very low level makes simulation of all the different agents' very computation intensive and time-consuming.

2.2 Innovation diffusion theory and Modelling human behaviour

In order to analyse the diffusion of heat pumps, a theoretical basis for the ABM is needed. Therefore a literature study into the different innovation diffusion theories is performed here.

The diffusion of innovations has been analysed for decades, with Rogers Diffusion of Innovation (DoI) (Rogers, 1962) as one of the well-known theories. In the DoI, the adaptation of an innovation takes the shape of an S-curve, where adopter categories are specified, starting with the innovators, who are the first to adopt, followed by early adopters, than the early majority, later majority and at last the laggards, the last group to adopt, see Figure 6.

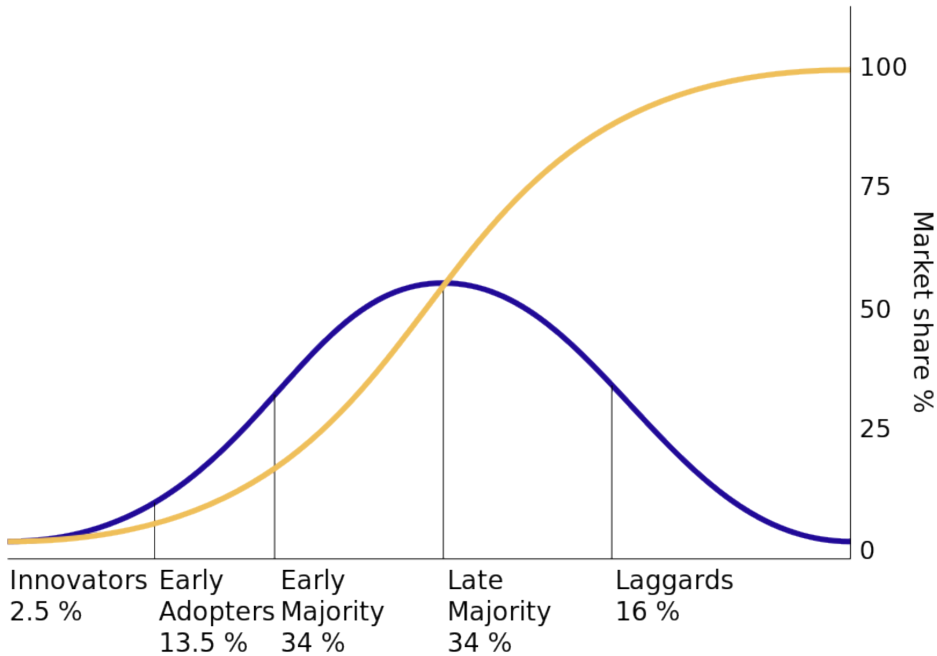


Figure 6: Rogers S-curve of innovation and the adopter categories (Rogers, 1962)

Rogers's adopter categories are still widely used today. The early majority doesn't buy anything before someone has done it first. The laggards, only buy something because it is absolutely necessary to do so, because the product to be replaced is simply not available anymore. The early adopters don't buy something for the technology or for the price, but they buy it for themselves, because they want to show people how well they are doing for themselves or the environment. According to Rogers (1962) the four major aspects of innovation diffusion are innovation, communication channels, time and the social system. The social aspect of diffusion is thus very important.

A lot of theories used the DoI as a starting point. Overall they can be divided into two sections: The mathematical theories and the psychological models.

2.2.1 Mathematical models

The model by Bass (1969) is a mathematical extension of Rogers pioneering work (Hlavinka et al., 2016). It is the most widely used theory on innovation diffusion, with over 7.400 citations on Google scholar at the moment of writing. The aggregate model by Bass is based on a differential equation; whereby the diffusion is dependent on an innovation factor p, imitation factor q and the currently installed base $F(t)$, see Eq. (1). Different technologies have different innovation and imitation factors. Typical values are around 0.3 for the innovation factor and 0.3-0.5 for the imitation factor (Mahajan, Muller, & Bass, 1995)

$$\frac{f(t)}{1 - F(t)} = p + qF(t) \qquad \text{Eq. (1)}$$

Another example (Eq. (2)) is the model by Fisher and Pry (Fisher, 1971), which now functions as the basis for the current S-curves being implemented into the Alliander model called ANDES (van Westering, Zondervan, Bakkeren, Mijnhardt, & van der Els, 2016). The ANDES model calculates the effect of the curves on the electricity grid with different scenarios.

$$f = 0.5\ (1 + \tanh\ (\alpha\big(t - t_h\big) \qquad \text{Eq. (2)}$$

Where α is half the annual fractional growth in the early years of diffusion, t_h is the time at which the diffusion has reached 50% and f is the fraction of the potential market that is substituted by the new technology.

Equation approaches as described above have their limitations, as is described by (Moglia, Cook, & McGregor, 2017). The limitations are caused by the fact that these models aggregate individuals or households into groups, like household size and location. This makes it impossible to include communication between individual households, describe accurately how household decisions are made and to include variability of household's preferences. The heterogeneity, which affects the diffusion of innovations (Kiesling et al., 2011) is not present. Even though the Bass model is partly based on Rogers DoI, it does not take into account the micro-level factors of adoption and communication, which is described by Rogers. Ting Zhang et al. (2011) also argue that environmental innovations do not follow the prototypical Bass diffusion curve because of long take-off times and diffusion discontinuities. Based on these arguments it is decided that the equation models are not suited for this research. Psychological approaches on the other hand, are more promising for ABM, as will be explained in the next paragraph.

2.2.2 Psychological models/ Decision making models

Contrasting to the mathematical models described above, psychological models do take into account the heterogeneity of customers and their choices, rather than assuming rational consumers. Over the years, numerous types of models have been created, see Tao Zhang & Nuttall (2011) for an overview. Of these models, the Theory of Planned Behaviour (TPB) is a commonly used framework for ABM (Kiesling et al., 2011; Moglia et al., 2017; Schwarz & Ernst, 2009; Sopha et al., 2013).

Other approaches are the Consumat approach (Janssen, Vlek, & Jager, 1999) and the Comprehensive Action Determination Model (CADM) by Klöckner & Blöbaum (2017). The CADM is an extension of multiple other models, among other things the TPB. It provides an interesting option for modelling human behaviour. However in none of the studies where CADM is chosen, ABM was used. Therefore, this framework is further left out of scope. Consumat is another suitable approach for ABM (Moglia et al., 2017). The choice for the right psychological model is difficult, as it is hard to estimate which represents human behaviour the best way. In this thesis, the TPB is the preferred. The justification is that the TPB deals with the connection between beliefs and behaviour (Karytsas & Theodoropoulou, 2014). Contrasting to the CADM model, it has been widely used for ABM as a theoretical foundation (Kiesling et al., 2011). Recent examples are Schwarz & Ernst (2009), Rai & Robinson (2015) and Sopha et al. (2013).

2.3 The Theory of Planned Behaviour

The TPB by Ajzen (1991) is a theory explaining human behaviour. In the theory three attributes determine the intention towards a behaviour: the attitude, subjective norms and the perceived behavioural control (PBC). It is an extension on the theory of reasoned action (also by Azjen) by adding the PBC. The intention to perform a certain behaviour is a central factor in the TPB. It represents the motivational factors that influence behaviour and shows indications of how hard an individual or group are willing to try and how much effort they are willing to put into the behaviour. The stronger or higher the intention, the more likely that the behaviour will be performed. In the TPB, intentions are assumed to capture the motivational factors that influence a certain behaviour; they are indications of how hard people are willing to try, of how much of an effort they are planning to exert, in order to perform specific behaviour.

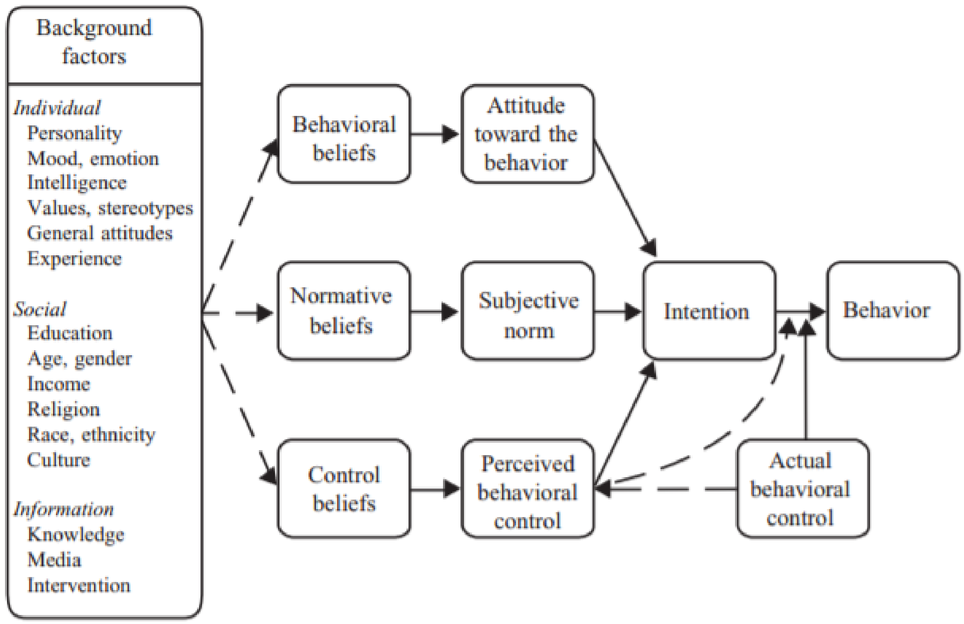


Figure 7: The theory of planned behaviour by Ajzen (1991)

The intention depends on the volitional control, which means that behaviour is at least to some degree dependent on some non-motivational factors, such as money, time, skills and cooperation of others. These factors represent people's actual control. This means that when a person has the intention and the actual control, the person should succeed in performing specific behaviour. An important note with the TPB is that the importance of the three attributes *attitude, subjective norm* and *PBC,* can vary across behaviours and situations (Ajzen, 1991). So in one situation only attitude might be sufficient for a behaviour to occur, whereas in other situations all attributes have an independent contribution. Azjen describes that each attribute is influenced by a salient belief. Behavioural beliefs have influence on the attitude, normative beliefs on the subjective norm and control beliefs on the PBC, see Figure 7.

Attitude

The attitude is about the evaluation of an individual towards the behaviour. This can be favourable or unfavourable. The behavioural beliefs that lead to the attitude favour the behaviours that have desirable consequences and vice versa. The beliefs do not only have subjective value, but also certain strengths. Combining all the behavioural beliefs, their subjective value and strength leads to the following equation:

$$A \propto \sum_{i=1}^{n} b_i e_i \qquad \text{Eq. (3)}$$

Where A is the Attitude, b is the strength of each salient belief, e is the subjective evaluation, n the number of salient beliefs and i the individual.

Subjective norm

Influence by the environment is the central aspect in this attribute. It is about the perceived social pressure to perform or not perform a behaviour. Normative beliefs are the basis for this attribute. Normative beliefs are about the likelihood that peers approve or disapprove a behaviour. In the below equation, no is the strength of each normative belief, m is the motivation to comply with the peer in question, n is the number of salient peers. The total subjective norm SN is the sum of the strengths times the motivation, summed over all peers.

$$SN \propto \sum_{i=1}^{n} no_i m_i \qquad \text{Eq. (4)}$$

Perceived behavioural control

The PBC is about the perceived ease or difficulty of performing the behaviour. It is influenced by control belief, which stands for the presence or absence of requisite resources and opportunities. The more resources and opportunities an individual believes to possess, and the lower the perceived obstacles, the higher the perceived behavioural control. The PBC is expressed with the control belief c, the perceived power p, summed over each belief n.

$$PBC \propto \sum_{i=1}^{n} c_i p_i \qquad \text{Eq. (5)}$$

2.4 Conclusion

The energy infrastructure system where heat pumps are a part of can be classified as a complex adaptive system, making it suitable for an ABM study. ABM is a flexible modelling technique that is capable of modelling the social and economic factors, instead of just the business case, such as the reports in 1.2.3. Furthermore, it uses bottom-up modelling in order to capture emergent behaviour. Typically, in diffusion studies emergent behaviour is present. With ABM, soft factors can be modelled, although this is difficult to do so. Another drawback is that finding the right level of detail can be challenging.

The sub question of this chapter "*What innovation diffusion theory should function as a basis of the model?*" Indicates theory is needed concerning innovation diffusion, of which a plethora is available. This sub question focuses on the **diffusion** part of the research question "*What is the influence of financial incentives on the **diffusion** of heat pumps in the Netherlands using Agent Based Modelling?*" Theory concerning innovation diffusion is essential for the ABM, as it forms the structure on which the model is build. Rogers pioneered with publishing his Diffusion of Innovation theory, in which diffusion follows a typical S-shaped curve due to the different adopter groups: Innovators, early adopters, early majority, late majority and laggards. Bass based his differential equation for innovation diffusion on Rogers theory. However, Bass's model and other pure mathematical equivalents lack the heterogeneity and micro-level factors that are so important for innovation diffusion. Therefore, psychological models are better suitable to function as a basis for the ABM. In this study, it is assumed that the Theory of Planned Behaviour sufficiently captures human behaviour. With the TPB, the heterogeneous aspects of households can be integrated into the model. The TPB assumes that humans have certain intention for a behaviour, which is influenced by an Attitude (what consequences result from this behaviour?), Social Norms (morals, what does the environment think?) and a Perceived Behavioural Control (am I convinced that I can indeed perform this behaviour?). The TPB forms the first essential part for the model. The second part concerns the factors influencing HP diffusion, which will be discussed in the next chapter.

3

Factors influencing HP adaption

In the previous chapter a theoretical basis is provided. In this chapter, the other part of the basis for the ABM model is discussed: the factors influencing HP adoption. As such, sub question 2 will be answered in this chapter:

Sub question 2: *1. What factors are identified in the literature to influence diffusion of HPs and should therefore be included in the model?*

Although there have not been many studies using ABM for heat pump adoption, there have been many studies testing which factors are relevant in household's choices. First a general overview of different groups of factors will be given in 3.1. The chapter is further structured as according to Dieperink, Brand, & Vermeulen (2004), who clustered explanations found for innovation diffusion in literature to five aspects: (1) decision making of the potential user (2) characteristics of the potential user (3) influences impinging on the household (4) technological and economic characteristics of the technology and (5) the macro context of the society at large. Next, they converted the factors into a framework. A simplified version of that framework is shown in Figure 8. As companies are out of the scope in this research, it is solely about household characteristics. In 3.2 the economic and technological aspects of heat pumps are assessed, such as efficiency, investment costs and other technology related subjects. Paragraph 3.3 targets the household's characteristics, thus the household's specific factors playing a role in their adoption choices. Subsequently 3.4 presents all environmental related aspects, such as policy measures and influence by the other households. Finally, 3.5 specifies what developments in the macro-context are important, such as awareness of climate change.

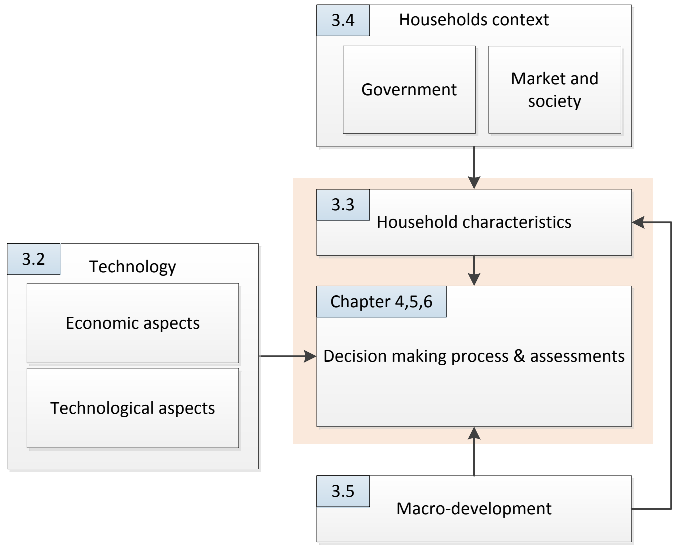


Figure 8: Simplified version of framework by Dieperink et al. (2004)

3.1 Literature overview

In Table 3 an overview of the literature on heat pump adoption is given. A division has been made between studies that specifically address heat pumps, studies that consider heating systems, Dutch studies and literature overviews. This table is used as basis for the rest of the chapter.

Table 3: Literature overview of factors influencing heat pump diffusion

Article	**Technologies**	**Country**	**Methods**	**Most important factors**
Studies considering HP specific (among others)				
Karytsas & Theodoropoulou (2014)	GSHP	Greece	Survey and logistic regression analysis	Age, education level, gender, income, information on RES, connections to industry
Burley (2017)	ASHP	UK	Case-study, interviews, survey and a literature review	Economy, Space impact, reliability, maintenance, visual impact, noise, understanding of HP
Snape et al. (2015)	HP: GSHP & ASHP	UK	ABM	Payback period, social observation, hassle factor

Hlavinka et al. (2016)	Ductless HP	Pacific NW USA	Stochastic simulation. Extensions of Bass-model	Economy, expenditures on advertising and installer training
Studies considering heating systems				
Sopha et al. (2013)	Electric- & Wood-pellet heating, HP	Norway	ABM	Fuel price, air quality, reliability, total cost, required work, decision strategy
Mahapatra & Gustavsson (2008)	District heating, wood pellet heating & HP	Sweden	Survey	Economy, reliability, communication with installers and peers, subsidies, age, information, need for a new system
Caird and Roy (2017)	Solar thermal hot water, HP & Biomass heating systems	UK	Survey	Environmental benefit, costs, pride, payback time, reliability, performance, advice
Sopha et al. (2011)	Wood-pellet heating	Norway	Survey	subjective evaluation of costs and functional reliability
Noonan et al. (2013)	Residential HVAC	Chicago USA	Spatial lag regression using sales data	Neighborhood effects
Michelsen & Madlener (2016)	Condensing boiler with solar thermal support, HP & Wood-pellet heating	Germany	Discrete choice model and logistic regression	Financial support, costs, psychological barriers (functioning of system + difficulty of getting used to system), environmental concern, knowledge
Dutch studies & HP or heating systems				
Dieperink (2004)	HP, CHP, boilers	Netherlands	Literature review, clustering and constructing a framework	Macro contexts, environment, economic aspects, technical aspects, decision making process,

				companies characteristics
Leenheer (2011)	Distributed energy technologies	Netherlands	Survey and conceptual model based on TPB	Environmental concerns, affinity with technology.
Other				
Heiskanen et al. (2016)	HP, solar PV, solar thermal, biomass heating	Europe	Literature review	Social influences, comfort and convenience, costs, recommendations by installers, promoting campaigns, policy
Friege et al. (2016)	Insulation activities	Germany	Survey and ABM	Homeowners age, attitude towards insulation and condition of the walls
Friege & Chappin (2014)	Energy efficient Renovations	N.A.	Literature review	Costs, comfort, environmental impact, incentive instruments

3.2 Household characteristics

Based on the literature provided in the previous paragraph, the most important factors concerning heat pump adoption are selected.

3.2.1 The economic, social and hassle factor

As mentioned in Chapter 2, the heterogeneity of households is very important. For a large part this comprises the demographics, but also the characteristics of the house and energy related subjects are relevant. The starting point for these characteristics is the study by Snape et al. (2015), as this also a study concerns heat pump adoption with ABM. The three factors used in that study, the hassle factors, economic factor and the social factor will also be used in this study. The calculation of the factors will be performed differently than in Snape et al. (2015).

Besides Snape et al. (2015) Almost all the articles in Table 3 have an economic or costs factor that plays a role, therefore it can safely be assumed that it is one of the deciding factors. The economic factor in Snape et al. (2015) is a simple calculation that is based on the savings and total investment of a heat pump. The savings are calculated by estimating the difference between the energy bill with a heat pump and the energy bill without one. Therefore, the *electricity usage* and *gas usage* are required household characteristics. The other variables needed for determining the payback time are mostly decided by the context, economic and technological aspects found in the other sections of this chapter, such as investment cost, subsidies, energy costs and efficiency.

3.2.2 Income

When looking at Table 3, one might not expect that income is an important aspect, as it is only mentioned once. It is however closely related to the cost related factors, as the higher the income, the higher the room for investment generally is. Income is a factor that has been found to be statistically significant in explaining heating system selection in multiple studies, as is shown by Karytsas & Theodoropoulou (2014). In ABM diffusion studies, the income can be part of the households characteristics (Sopha et al., 2013) or it is modelled as a decision factor (Palmer et al., 2015; Zhao, Mazhari, Celik, & Son, 2011). Either way income is assumed to play a huge role in the decision for heating systems in the literature.

3.2.3 Social factor

Logically, the social network is also a largely based on the context. Therefore, a comprehensive description can be found in 3.4.1. Household characteristics relevant for this factor are the number of connections. The *household group* to which the household belongs to is relevant as well, which is described in 3.2.6.

3.2.4 Hassle factor

Economic and social factors are common in diffusion literature, as these are also relevant for other technologies. The hassle factor however, is less present, but very relevant for heat pumps. Heat pump adoption involves a lengthy disruptive installation, takes up additional space and generates excessive noise, which are unpopular with end-users (Balcombe et al., 2013; DELTA, 2012).The hassle can also originate from an obligation to comply with regulation, such as obtaining certain certificates, an assessment or meet heating emitter requirement (Snape et al., 2015). Another way to interpret this is by the required maintenance as is described by (Sopha & Klöckner, 2011). End-users could think that a heat pump requires a lot of work concerning operation and maintenance.

3.2.5 Environmental benefits and concern

What is not incorporated in the model by (Snape et al., 2015) is the environmental benefit. A heat pump only uses electricity, assuming future hybrids use electricity and not (bio)-gas. Although most electricity in the Netherlands is grey, the average CO_2 per kWh is more than five times lower than the CO_2 emissions per m^3 gas (Otten & Afman, 2015).The reduced carbon footprint per household can already be significant, as can be seen in Box 1. When it is assumed that the average emissions of electricity will decrease due to more renewable energy, the carbon footprint will even be better. The environmental concern represents that attitude of households towards the environment. This is an important aspect for the division of household groups in 3.2.6

Box 1: Example calculation of reduced carbon emission when a GSHP is adopted

For a household of a family with two children under the following assumptions:

Yearly electricity usage: 4600 kWh*	Total yearly gas usage: 1720 m³*
CO_2 per kWh: 0.355 kg**	CO_2 per m³: 1.875 kg**
COP GSHP: 4	1 m³ = 9,769 kWh

Without HP: 4600 kWh × 0.355 + 1720 m³ × 1.875 = 1633 + 3225 = 4858 kg CO_2
With GSHP: 4600 kWh × 0.355 + ((1720 m³ * 9.769) / 4) * 0.355 = 1633 + 1491 = 3124 kg CO_2
This is a reduction of 1734 kg CO_2 emissions or 36%!

*averages from milieucentraal.nl
**Index from 2013 (Otten & Afman, 2015)

3.2.6 Household groups

An important aspect of households is the household group to which they belong. This forms the basis of the weights (weights are used in 6.5) that the households have for each factor. The groups are based on characteristics called *mentality*, from the EDM database. The mentality model was developed in 1997 and is updated and improved every year (Motivaction, n.d.) In total, there are 8 groups plotted on two axes: social status and values. Based on this model, a segmentation is made based on sustainability, energy, energy saving and openness to innovation and renewal (Randsdorp & Schoemaker, 2014). As is presented in Figure 9, this led to 4 groups, that each has a different perspective towards the environment and technology. The reason that the four groups based on a segmentation is used instead of the mentality groups is because the segmentation focuses on households motives for sustainability. Because heat pumps is a sustainable measure, the segmentation is believed to be more suitable for the model.

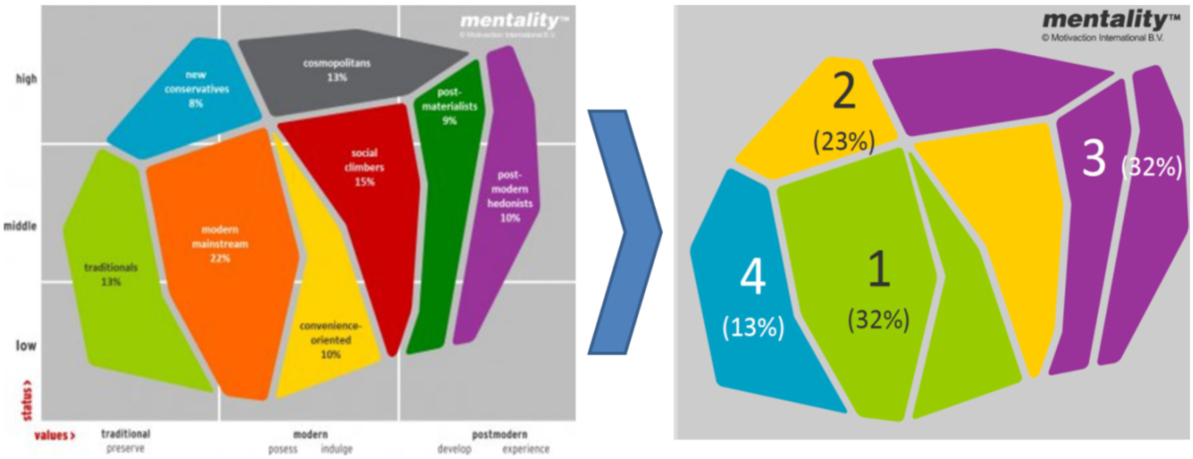


Figure 9: from mentalities to household groups

<u>1: Unaware Energy users</u>

The environment and technology are not subjects that households in this group care much about. The motto "my behaviour does not have an influence on the environment" is common here and the energy-label of products is not important. It is not surprising that this group is not eager to pay extra for renewable energy. Costs and convenience on the other hand are very important. This makes this group very hesitant towards heat pump adoption, unless it is made very convenient and cost-effective. Based on this description, the unaware environmentalists will likely be part of the late majority and laggards (Rogers, 1983) Almost a quarter belongs to this group in the Liander region: 24,7%

<u>2: Pragmatic Comfort Seekers</u>

Contrasting to the environmentally unaware, technology is very important. They believe technology will give them a higher comfort level. They rather have a comfortable house environment than a low energy bill. Although the environment is not something they are busy with, they do believe technology will improve the environment. This group slightly more eager to invest in heat pumps than group 1, as long as it improves their comfort, and with an acceptable pay-back time. 23,3% of households are part of this group in the Liander Region.

<u>3: Environmentally aware improvers</u>

These are the environmentalists, aware of the climate change and the damages of humanity towards the environment. This is the group that pays extra for sustainability and is interested in innovative technologies. A basic level of comfort is important, as long as this does not increase the costs too much. Of the four groups, it is most likely that this group adopts first, partly because the average income of this group is high. They can be called the innovators or early adopters, as depicted by Rogers (1983). The group is the largest in the Liander region with a share of 42,7%.

4: Faithfull environmentalists

Similar to group 3, the faithful environmentalist care about the environment. This group are the traditionalists, mainly 50+ and a low average level of education. They do their best to help the environment where they can, but because their knowledge and resources are limited, they don't know exactly how to help the environment. Technological advancement is something they think is complex, and therefore they don't use technological advancements as a way to become more sustainable. Heat pumps is not something this group would invest in if they payback time is acceptable, and if they are certain that it is the right thing to do. This group is also very concerned with its neighbourhood, so therefore the neighbourhood effect will be important for this group. Around 9,3% of the households belong to this group.

Table 4: Overview of the household groups

Group	Rogers	Share of total households	Cares about	Cares less about
Unaware environmentalists	Late majority, Laggards	24,7%	Costs	Environment
Pragmatic comfort seekers	Early majority, late majority	23,3%	Comfort, technology, status, costs	Environment
Environmentally aware improvers	Innovators, Early adopters	42,7%	Environment, technology	Costs
Faithful environmentalists	Early adopters, Early majority	9,3%	Society, costs environment	Status, technology

3.3 The economic and technological aspects of a heat pump installation

As heat pumps can be classified on many levels, the choice on which heat pump types to include in this thesis is discussed, in 3.3.1. Next is the financial business case, which plays and important role in the choice for a heat pump as is described in the previous paragraph. Therefore the economics aspects of heat pumps are discussed. It answers how heat pumps prices develop over time due to learning effects and provides on overview on the complete investment of a heat pump. This is handled in 3.3.2 and 3.3.3.

3.3.1 Selection of the heat pump types: HHP, ASHP and GSHP

Considering the complete spectrum of heat pump types, they are mostly specified by the energy source and the energy sink. A heat pump can retrieve its energy from air, water or the soil (the source), and it can deliver the warmth as hot air or water (the sink). Further distinctions can be made by the water source (ground or surface water), whether the system is open or closed and whether the loop is spiral, vertical or close to the surface. For an overview of GSHP, one is advised to look into Mustafa Omer (2008). Below a short description per heat pump type is given, as well as a description concerning the soil types and the relation with heat pumps.

3.3.1.1 Air-to-Air (ASHP)

The air-to-air heat pump is an outdoor unit that uses the outdoor air as a heat source. This type of heat pumps is relatively cheap, and is quick and easy to install. A Disadvantage is the lower efficiency of this system on cold days. A back-up is also needed. Because the heat sink is the indoor air, there is no heat release system needed. Therefore, this type is suitable if there is no heating release system present.

3.3.1.2 Air-to-water (ASHP)

The outdoor air is used to heat water, which can be used for heating purposes and tap water. The efficiency is dependent on the outdoor temperature, which means that low temperatures can lead to a low efficiency. Low temperature heating systems require other heating release systems than the conventional radiators in place in most households.

3.3.1.3 Hybrids air-to-water with a gas-boiler (HHP)

This type of heat pumps is essentially an air to water heat pump combined with a conventional gas boiler. Depending on the outside temperature and heat demand, the heat pumps and gas-boiler work together to heat the house. This heat pump is typically suitable in houses that do not have low temperature heating release systems and good insulation yet installed. Therefore, this seems to be a promising option for many existing households. The savings are around 25% percent and a household is still dependent on the gas prices. Hybrid heat pumps are gaining popularity and could be adopted on a large scale (Dutch Heat Pump Association, 2013)

3.3.1.4 Water-to-water (GSHP)

This type of heat pumps is the most efficient, due to the constant temperature of ground water. Other advantages are the relatively small system, it can be used for cooling and the water pumped up can also be used for flushing the toilet. A large downside is the huge investment costs, which are dependent on the depth of the water. Another water source, such as a river could also be used. The applicability is thus very dependent on the location.

3.3.1.5 Ground-to-Water (GSHP)

Here the heat from the underground is used as a source. The ground temperature is very constant; therefore the performance of these systems is constant as well. The soil type does have influence on these temperatures. A disadvantage is the higher investment costs. Adding to the costs of the heat pump installation are drilling costs. The insulation of the house also needs to be good, and low temperature release systems need to be in place. The drilling, upgrading the insulation and changing the radiators do not only cost a lot, but also require a lot of work. Two types of pipe systems are available: horizontal and vertical. For horizontal systems a surface of 200 to 400 square meters is needed, but the excavations work is less profound than for vertical piping systems. The average performance of vertical systems is higher, because the temperature of the ground is more constant than the horizontal systems, where the ground can cool down in colder periods.

3.3.1.6 Heat pumps and soil types

There are three soil types in the Netherlands (as well as in the Liander Region): clay, sand and peat. Technically, heat exchangers can be applied on each soil type. However, the maximum heat extraction can differ with different soil characteristics such as the thermal conductivity. The conductivity of a sandy soil is for instance better than peat or clay, which can result in significant differences for the length of the pipes (Krogt, 2011). Some households may not be advised to adopt an GSHP for this reason. On the other hand, it is still possible for each household to adopt irrespective of the soil type. Furthermore, it is unknown what soil types the households have, and calculating the dimensions of a heat pumps is a complex calculation already. For these reasons, the soil types are not included in this thesis.

3.3.1.7 Justification of the selection of ASHPs, GSHPs and HHPs.

As mentioned in 1.2.2, not all types of heat pumps will be taken into account separately. Heat pumps are generally classified as either ASHP or GSHP, and this formed the starting point of this research. GSHPs are not only heat pumps that use the soil as a heat source, but also surface and ground water. In the descriptions above, the heat sink can be either air or water for ASHP. Although this has influence on the efficiency and design of a heat pump installation, it is chosen to group this into just ASHP. Furthermore, there will be no soil characteristics used in this study, which makes it difficult to assess whether a household can install a water-to-water heat pump. Hybrid and air-to-water heat pumps have very similar characteristics, as they both are air sourced. However, there is an important difference in the applicability. HHPs can be applied in houses without the need for further investment in the insulation and/or heating release systems, due to the use of the gas-boiler. This is not the case for standard ASHP. Therefore, it is chosen to include three types: (1) hybrid heat pumps, (2) air sourced heat pumps and (3) ground source heat pumps.

3.3.2 Learning or experience effects

When a technology matures, the complete sector gains more experience, the more the technology is applied. Experience curve effects/learning curve effects express the relationship between equations for experience and efficiency gains and investments in the effort. The experience is based on standardization, labour efficiency, specialization, better use of equipment, product redesign and innovation. For innovations, this can lead to drastic cost reductions. A good example is the drastic price reduction of solar panels of 70-80% in the past decade (IRENA, 2014). To assess the position of heat pumps in the experience curve is useful, as such future costs reductions can be incorporated in the model. Overall the learning rates for energy supply technologies range between 5% and 20% (Weiss, Junginger, & Patel, 2008)

Heat pumps have been around for decades, so unlike solar panels or electric vehicles it cannot be considered a recent discovery. For the UK, DELTA (2012) does not expect large cost reductions for GSHPs, because the technology is considered mature and there is little margin at installers because the instalment process is complex. They expect the costs to drop with 20 percent from £16.300 in 2012 to £13.100 in 2045. Contrasting to GSHP, ASHP dimensions are quite general. GSHP installations have to be altered according to the house characteristics, expected energy use and heat pump efficiency. Because the one-size-fits-all principle suits ASHP to some extent, ASHP can possibly benefit from economies of scale. Percentage wise the cost reductions are not as high compared to GSHP, as DELTA (2012) estimates the costs to drop with 22%- from 2012 to 2045. On the other hand, one can look at heat pumps from the perspective of the definition of innovation by Rogers (1983, p14) '*An innovation is an idea, practice, or object that is perceived a new by an individual or other unit of adoption*'. So it does not only matter how long the technique has been around, it matters how new it is to the people. For many people in the Netherlands heat pumps are very new, as the majority is locked-in with gas boilers. The same is true for the majority of installers. In a national newspaper it is confirmed that there are still problems with heat pumps, partly due to faults during installations or dimensioning performance (Meijer, 2017). Based on price data in Switzerland, Weiss et al. (2008) estimate cost reductions of 25 to 42% each time the capacity doubles for heat pumps, assuming that production costs follow prices adequately. However, they note that this assumption is subject to considerable uncertainties, as the data availability was poor. Next to the costs, experience in the sector also leads to improvements of the COP, the same study estimates the performance to improve by 13.8 percent (+- 1.8) every time the capacity doubles. COP values are however bound to a maximum of around 8.8 according to standardized test procedures[4]. DELTA (2012) estimates that the performance of ASHP improves

---

[4] The standardized test procedures are handled by the Dutch organization NEN and can be found at https://www.nen.nl/NEN-Shop/Norm/NENEN-1451122013-en.htm

slightly, from 2.5 in 2015 to 3 in 2050 and for GSHP from 2.5 to 3.8. This is specified for retrofit, for new houses the numbers are slightly better. The effect of improved performance of heat pumps is twofold. The first concerns higher savings compared to a gas boiler, and thus a shorter payback time. A second advantage is lower CO_2 emissions, as a lower amount of electricity is needed.

3.3.3 Investments related to insulation and heat release systems

The business case for heat pumps thus improves slightly as the technology improves, however, the costs of heat pumps is not the only investment necessary when deciding to adopt. Two other parts of the house are important: insulation and the heat release system type. With the latter is meant whether heat is released through radiators, floor heating or wall heating. Rebuilding existing houses towards all-electric houses is very costly (ECN, 2016a). Furthermore, to let future heating systems comply with sustainability targets and regulation (EPC, energy label, BENG), insulation is a central aspect (Bakkeren & van der Els, 2016). The reason that both insulation and the heat release system are important is because of the low temperature heat that is supplied by a heat pump. Currently, houses are generally poorly isolated, especially older houses. Would the EPC level of most houses remain the same when a heat pump is installed, a lot of heat will be lost, thereby reducing the efficiency of heat pumps. At the same time radiators present in most houses nowadays are not suitable for heat pumps, since the heat radiaton surface of the radiators is too small for the low temperature heat. Unsurprisingly, the extra investment costs are significant. In current literature, the extra costs of these investments are barely taken into account. In the study by Snape et al. (2015) the insulation aspect is mentioned, however it is only used as a part of the *hassle factor* (3.2.1). Sopha et al. (2013) take the subjective evaluation of the total costs of investment derived from an empirical study, instead of the real value. Insulation is not explicitly mentioned as part thereof.

3.4 Household context: Social influences and financial incentives

In the previous paragraphs, the households characteristics and important factors in their decision are handled, as well as the technological and economic aspects of the technology itself. The system is not yet complete however, what is missing, are the factors from the environment that play a role. How to peers, installers and media influence household's decision making? This is the social influence, and is discussed in 3.4.1. Another environmental aspect are the financial incentives, which make up the main aspect of the research question. They are listed in 3.4.2

3.4.1 Social influence

3.4.1.1 Influence of peers

The importance of social influence, thus the influence of recommendations from friends, neighbours or installers on households decisions is stressed in many studies (Heiskanen & Matschoss, 2016). The social system is one of the characteristics of innovation in Rogers DoI (Rogers, 1983). Part of that social system is the communication structure, which Rogers (1983, p25) defines as 'The differentiated elements that can be recognized in the patterned communication flows in the system'. In the Bass model the neighbourhood effects are present as well, under the imitation factor (Bass, 1969).

Kiesling et al. (2011) provides a useful overview of modelling the social influence and differentiates it between micro-, meso-, and macro-level social influence. The micro level is mainly about the Word-of-Mouth (WoM), thus locally through pairwise communication links. The meso-level social influence concerns the influence from the immediate social environment. This is associated with group conformation, herding behaviour and social comparison. The macro-level involves global interactions, such as network level opinions and learning effects based on cumulative sales (see 3.3.2). Macro-effects are studied less common than meso- and micro-level effects.

Social influence is exerted throughout the social network of a household. To construct such a network, a suitable network topology is needed. The network topology of the consumers social network involved in the consumers decision making has a large impact on innovation diffusion (Kiesling et al., 2011). Common network topologies are random, regular (clustered or spatial), a Small-World-Network (SWN) or scale-free. The type of network topology can have a big influence on the diffusion. Random networks tend to favour the spread of information quicker and are more associated with quicker adoption, whereas in markets with strong meso-level social influence, the diffusion is more likely and faster with clustered topologies. Besides the topology of the network, the social influence diminishes as time progresses for PV diffusion (Graziano & Gillingham, 2014). Whether the same is true for heat pumps is unknown.

Snape et al. (2015) used a spatial network topology for modelling heat pump diffusion, Sopha, Klöckner, & Hertwich, (2010) found that the Small-World-Network (SWN) was the best representation for the social structure for modelling heat system diffusion in Norway. It is also used for modelling PV diffusion (Palmer et al., 2015; Rai & Robinson, 2015) and water savings innovation (Schwarz & Ernst, 2009). The Scale-free network topology is not as often used as the SWN, however, is serves as an optimal structure for knowledge transfers for innovation diffusion (Lin & Li, 2010) and is used multiple times as is shown by (Kiesling et al., 2011). Is also served as a topology for analysing the behaviour of consumer lighting (Chappin & Afman, 2013). The scale-free network will be the network topology used in this thesis.

3.4.1.2 Influence of installers

Studies have shown that the main source for information for building owners are installers, and their recommendations have significant weight in the choice of several building systems or components (Heiskanen & Matschoss, 2016). The knowledge level of installers can thus have a positive influence on the overall adoption process. However, the authors also stressed that the installers influence isn't necessarily positive, as poor service levels, lack of knowledge, and lack of trustworthy installers can results in negative experiences for households. Mahapatra & Gustavsson (2008) also found that installers were the most important communication channels for information on heating systems in Sweden. Aside from the information, the capabilities of installers can even alter the diffusion process. Negro, Alkemade, & Hekkert (2012) provided an overview with factors underlying slow diffusion processes. A quickly growing sector could lead to a shortage in trained personnel. In both the PV and micro-CHP industry these factors were found to have an influence on the diffusion. The strong influence of installers should also be part of policy instruments, as these policies should incentivize installers to advise homeowners to have insulation installed (Friege, Holtz, & Chappin, 2016)

3.4.1.3 Influence from (social-) media

Besides installers and peers, households retrieve information through the media. An aspect which is one of the factors of the Bass model (Bass, 1969). Nowadays this effect might even be stronger, due to the presence of the internet and social media.

3.4.2 The financial incentives for heat adoption

3.4.2.1 Subsidies

Currently there are subsidies available for heat pumps. In the Netherlands this is called the ISDE[5]. This is a subsidy for especially for heating systems, including solar boilers, heat pumps, biomass furnaces and pellet heaters. The budget per application depends on the power of the system. Under 3.5kW the subsidy is 1000 euro, 3.5kW to 10kW is 2000 euro and above 10kW the subsidy is increased with 100 euro for every extra kW. The total budget for 2017 is 70 million euros (RVO, 2016). This is not a large budget, when considering that it is for multiple technologies and for both private individuals and companies. Even if the average subsidy is 1000 euros (which is low) per application, this means 70.000 individuals and companies can apply per year. Heat pumps cost 5000 to 15000 euros on average, excluding insulation costs and costs for other radiators or

[5] Investerings Subsidie Duurzame Energie, which translates to Investment Subsidy Renewable Energy.

floor/wall heat which are likely to at least double the total costs. The overall high investments needed for heating systems do not make it very surprising that around 80% of tax discounts and subsidies is used by the people with the highest incomes (Vergeer, 2017). Compared to the SDE+ budget of over 1.2 billion euros in 2017 (Ministry of Economic Affairs, 2016b), a subsidy for renewable energy production, the ISDE budget is minimal. The budget for the SDE+ in the coming years is growing to over 3 billion euros in 2021 (Ministry of Economic Affairs, 2016b), however, the ISDE budget is published on a yearly basis, so future developments are unknown. Contrasting to ISDE, for SDE+ it is clear how the subsidy is financed, as this is by a tax called ODE, which is increased every year until at least 2023 (Ministry of Economic Affairs, 2016c) . Although the plans are not public for ISDE, it is likely to assume that the subsidy budget will steeply increase in the coming years, to stimulate the shift away from gas boilers.

Table 5: ISDE compared to SDE budgets. Value in million euros. Sources: (Ministry of Economic Affairs, 2016b) and (RVO, 2016)

Year → Subsidy	2015	2016	2017	2018	2019	2020	2021
ISDE	0	60	70	?	?	?	?
SDE/SDE+	314	1057	1267	1693	2316	2993	3050

3.4.2.2 Energy taxes and VAT reductions

In the energy bill two taxes are included that take up a substantial amount in the electricity and gas prices. The taxes on electricity are even five times higher than gas (Rooijers, Schepers, & Cherif, 2015). To promote sustainability, whereof heat pump adoption, the taxes on gas should be just as high as electricity. The first tax is the Energiebelasting (EB), or energy tax. This is the regular tax that every household pays for using electricity and natural gas. One does not have to pay this tax when the household produces its own electricity or biogas. Another, lesser known tax is the Opslag Duurzame Energy (ODE), which roughly translates to Increment Renewable Energy. This is an extra tax next to the EB. This tax was introduced in 2013 and goes directly into the subsidy budget of the SDE+. Buyers of heat pumps thus don’t have the benefits of using the SDE+ subsidy, but they do have to pay the tax. This tax will increase with a steep curve the coming years, to make sure there subsidy budget is big enough to stimulate renewable energy development. The development of the taxes can be seen in Figure 10 and Figure 11. These taxes largely determine the price of gas and electricity.

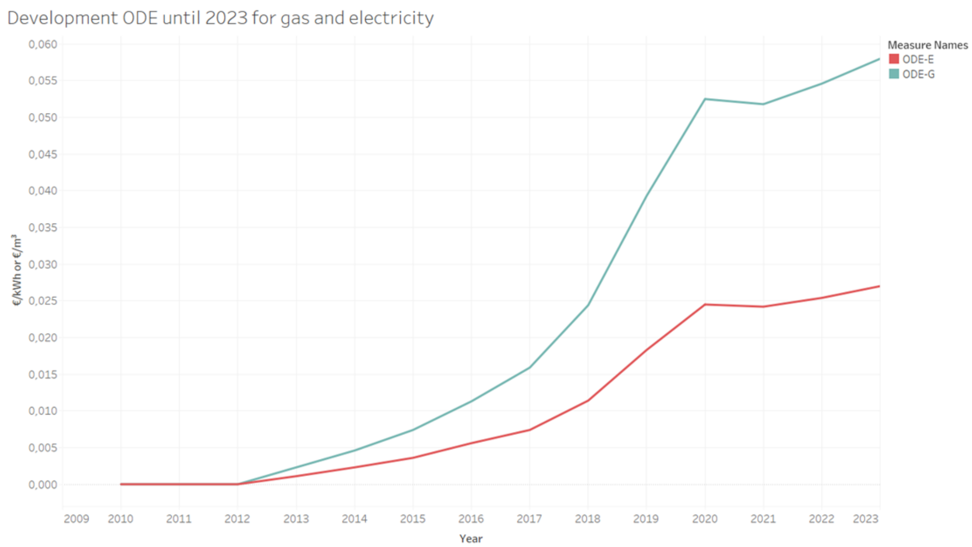


Figure 10: ODE developments from 2009 until 2023

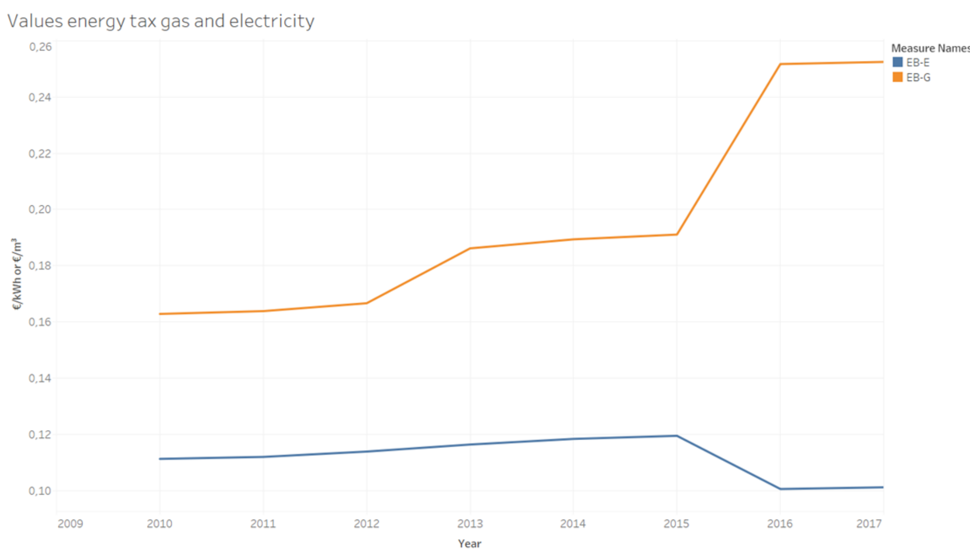


Figure 11: Energy tax developments from 2010 to 2017

Another type of tax is the VAT on heat pumps. Currently, heat pumps cost significantly more than gas-boilers. This is partly due to the fact that both are taxed at the VAT tariff of 21% (Dutch Heat Pump Association, 2013). Reducing this tariff is a measure to stimulate heat pump adoption.

The government can thus influence the electricity and gas-prices by taxing them. Another way to exert influence is by changing the VAT tariff, as the proposed by the DHPA (Dutch Heat Pump Association, 2013)

3.4.2.3 Regulation of the insulation and energy-label requirements

Another measure by governmental organization is regulation. One of the most important types in this research is regulation concerning insulation. Following European directives energy-labels were introduced for all houses in the Netherlands. The goal is to assign energy efficiency directly to a house, so that its owner and residents are more aware of their energy use. At first, the government assigned a temporary energy label to all houses. When the house is sold or rented to new people, a definitive energy label is required. Houses that have not been sold since the introduction of energy labels could thus not have an accurate energy label yet. The measure is for all houses, newly build and existing buildings.

Another insulation related type of regulation the Energy Performance Coefficient (EPC). At the moment, this is solely for new houses. The EPC can be improved by upgrading the insulation levels, or by using renewable energy sources. The lower the value, the better the EPC Currently, the maximum value is 0.4. In 2020, it will be replaced by BENG (*Bijna Energie Neutraal Gebouw)* (Bewustnieuwbouw.nl, 2016), which is an even more strict type of regulation. At the moment the existing buildings don't have to bother EPC or future BENG norms, however, it is not unlikely that the government will impose alike requirements for existing buildings in the future, thereby applying pressure on households to improve their insulation or adopting renewable energy technologies. Therefore this could influence the adoption of heat pumps.

The energy-label and EPC are very important. When a house has a low energy label, and thus bad insulation, heat can easily be lost. Therefore the efficiency of HPs is dependent on the insulation of the house. Insulation is generally a very effective measure for households to reduce their consumed energy (Friege et al., 2016). These measures alone will not incentivize households to invest in insulation. The reason that even though households know the benefits of insulation but still don't invest in insulation, is because there are non-economic motivations and barriers that are mostly underestimated by policy makers (Friege et al., 2016)

Next to the insulation related regulation, the government can implement more stringent measures, which will force households into disconnecting from the gas-grid. For instance, a five year period could be given to all households. The government could give extra subsidies for the households who won't have sufficient resources.

<u>Regulation as a financial incentive?</u>

The BENG regulation might not sound like a financial incentives on itself. However, in this thesis it is considered as one. The idea is that once households do not comply with BENG norms, they will receive a financial penalty in some way.

3.4.2.4 Lowering the upfront costs by leasing or lending constructions

As mentioned, the costs are the largest barrier to heat pump adoption. Therefore it is interesting to see what measures aside from subsidies could change the adoption rate. One option is a lease construction. There are various potential types of leasing constructions for heat pumps, and some are already in use in several countries (Heiskanen & Matschoss, 2016), as well as the Netherlands. Multiple types of organizations could do this, such as DSOs, banks and energy suppliers. It could also be a new type of organization, for instance an energy service company. The options for households can be divided into buying, leasing or lending. Leasing means that the households pays a fixed price (with interest) and has the chance to buy the heat pump at the end of the contract. Mostly these are long term contracts and could costs households more in the end than buying the complete heat pump in the beginning. Lending means that the household will never own the heat pump, but pays a fee per time period.

3.5 Conclusion

Looking back at the research question *"What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using Agent Based Modelling?"* this chapter aims to provide insight in the possible financial incentives for stimulating heat pump diffusion, as well as all other factors that play a role. The research question to be answered was "*What factors exert influence on the diffusion of heat pumps and what other aspects should be included according to literature?"* These factors give shape to the attributes of the theory of planned behaviour.

The financial considerations of a household are mentioned and used in almost all innovation literature. This concerns factors as the payback time, savings and the investment cost. The government can stimulate heat pump adoption through multiple financial incentives such as subsidies, energy prices, VAT on heat pumps and through regulatory measures such as increasing the insulation requirements (EPC or BENG). Leasing or lending and learning effects can also have an effect. The choices of households however are not solely dependent on government's measures. Social influence from installers and neighbourhood are relevant, as well as the hassle of an installation. The hassle concerns the inconvenience of heat pump installation, such as the drilling possibly improving the insulation and radiators. Compared to gas boilers, a lot has to change in a house before heat pumps can be used, especially with ASHP and GSHP. Furthermore, the environmental benefit plays a role. Considering the households demographics, households are classified into four groups, which determine their view on renewables. Income is another demographic which could be an indicator for adoption of heat pumps. Logically, not all households evaluate these factors equally; some value the environmental benefit more than the costs, where others mainly consider the cost aspect of installation. These perceptions follow from the household groups.

The heat pump types that will be used in the model are Hybrid Heat Pumps (HHPs), Air Sourced Heat Pumps (ASHPs) and Ground Sourced Heat Pumps (GSHPs). Influence on households decisions can come from either the social influences, such as direct peers, but also media and advice from installers. The other contextual factor are the financial incentives. In this thesis they are in the form of subsidies, energy prices, leasing and the BENG norms for isolation.

Part II

Chapter 4: The conceptual model of heat pump diffusion

Chapter 5: The storyline of the heat pump diffusion model

Chapter 6: Model formalization and implementation

Part I consisted of two main subjects: innovation diffusion theory and factors influencing heat pump adoption. From *Chapter 2* we know that the theory of planned behaviour (TPB) will be used in an agent based model. In *Chapter 3* a literature overview was presented with all relevant factors that play a role in the heat pump adoption. By themselves these chapters will not lead to an ABM, therefore the goal of Part II is: *Merging the information from the literature review in Part I towards a complete description for the ABM.* Part II as a whole aims to answering sub question 3:

How can the innovation theory and factors from question 1 and 2 be combined into an ABM model?

Part II is divided into three chapters. Chapter 4 provides the conceptual model, which concerns all elements that are part of the system of heat pump adoption in the scope. Thus what are the agents, what is part of the environment, what interactions take place within the system and also the time frame. When the system is known, we continue with the process of the model in Chapter 5. The basis process of the model will be explained, as well as all steps a household and the environment goes through in a single time step. This chapter tells the story of the model. The following step is formalizing all parts of the system and process into pieces that can be implemented into the model, which is the subject of Chapter 6. This concerns the explanation of how the model is setup (both agents and environment), how the decision factors leading towards an intention is calculated. Also the perceptions of households and stochasticity in the model are handled. Finally, Chapter 6 ends paragraphs concerning assumptions made before and during the model implementation and verification.

4

The conceptual model of heat pump diffusion

In this short chapter, the conceptual overview is presented. This encompasses a description of the entities of the model in 4.1 and the interactions between entities in 4.2.

4.1 Description of the systems entities

In the first part all elements for the system are described shortly. There are mainly three **actors in the system**: the households, the installers of heat pumps and the government. Of the households, only the house-owners in the Liander region are taken into account. These households make decisions on their heating system, more specifically, whether they will adopt a heat pump. Therefore, the households are the central elements in the system and are thus the agents in the model. Another actor concerns the heat pump installers. When there is reason to, households consult these installers, who form a valuable source of information for the households, as could be seen in 3.4.1. For simplicity reasons the installers won't be modelled as agents, but as the environment. Modelling behaviour of the installers would require another literature study and interviews, which is beyond the time available for this thesis. Furthermore, the focus here is on the households behaviour. Modelling installers as the environment instead of agents themselves reduces the dynamics. And just as with households, installers are different and give different advice. Most installers in 2017 are solely focused on gas boilers, thus it could be interesting to see how they react to the financial incentives. In the model, the installers have the function here that can they steer households into the direction of heat pumps, by making them aware of the technology. Another actor that is part of the environment is the government. The government has the means to stimulate heat pump adoption. This is expressed in the model in form of subsidies, EPC requirements, and energy prices.

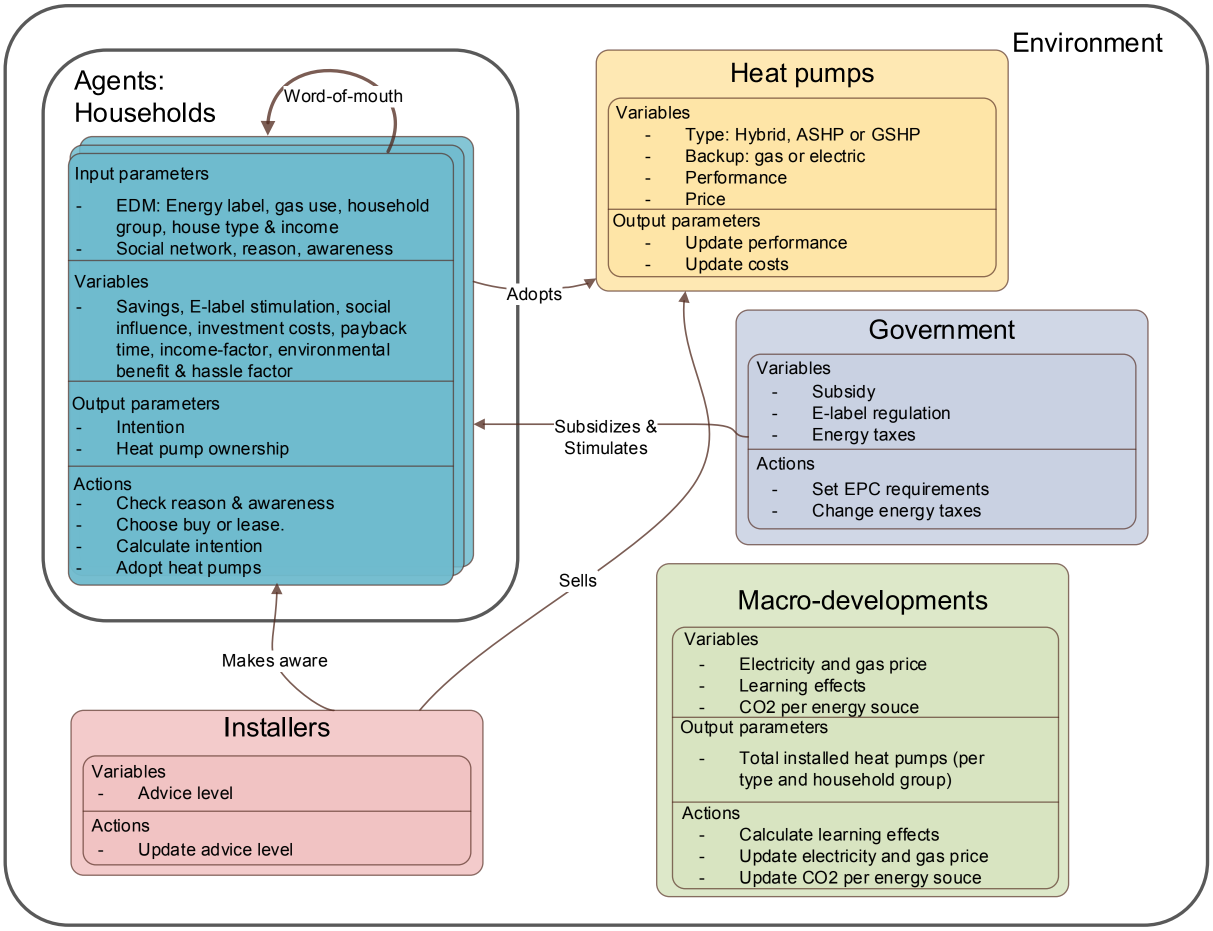


Figure 12: Conceptual model. The interactions can be seen, as well as the input parameters, variables, output parameters and actions.

The heat pumps represent the **technical component** of the system. Firstly, this is about the different types of heat pumps: hybrid, AHSP or GSHP. The second component is about the insulation. All households have certain level of insulation, which is important in the total energy required for heating. The third aspect is the heating release system. These are the radiators, floor or wall heating. Common radiators connected to the gas boilers can't be used for heat pumps, thus another type of heating release system is necessary.

The environment is not limited to the government and installers, but also includes the macro-economic influences from the market. The learning effect is a good example here. The electricity and gas prices are not solely determined by the government, but also by the market. The market will not be modelled as such, but changes in the gas prices could be explained in in this way.

Figure 1 holds the most important elements of the model, and will be further specified in Chapter 5 and 6. As can also be seen in Figure 12, the households (Agents) have 8 variables in total: Savings, Energy-label stimulation, social influence, investment costs, payback time, income-factor, the environmental benefit and the hassle factor. These 8 variables will from now on be referred to as the (8) decision factors. They are described as follows.

1. Savings: the expenditures that a household would have if it would keep using a gas boiler subtracted by the expenditures of a situation with a heat pump instead
2. Energy-label stimulation: Stems from a hypothetical situation where the government puts pressure on households to improve their energy-label
3. Social influence: originates from the social network of the households. The more peers adopt heat pumps, the higher this factor will be
4. Investment costs: a factor representing the perceived value of the total upfront investment costs to be fulfilled by a household.
5. Payback time: The number of years it takes before the household's total investment for the heat pump is payed back. Dependent on the savings and investment costs
6. Income factor: Represents the income level of a household
7. Environmental benefit: A factor that represents the amount of reduced CO2 emissions when a heat pump is adopted compared to the old situation with a gas boiler.
8. Hassle factor: The inconvenience the implementation of a certain type of heat pump brings.

All the decision factors follow from the literature in Chapter 3. Together, the decision factors will lead to a certain intention value which determines if a household will adopt a heat pump or not. The latter is expressed in the output parameters. How these factors are calculated, can be found in Chapter 6. In the agent the installers, government and heat pumps are not specific entities, but are part of the environment. This means that they will be described in the so called *global* variables in Netlogo. One will thus not see an installer be explicitly modelled as such, rather the collective knowledge level of installers at a certain time is modeled as a global variable. This also holds true for the heat pumps and government. It does however give a better overview by seeing them as separate entities, which is why they are visualized as such in Figure 12.

4.2 Interactions between the entities

One interaction in the model can be seen above the households in Figure 12. Logically, households interact. They do this within their social network, through *word-of-mouth*. The households make a decision concerning heat pumps, and in the end, can adopt a heat pump. The installers do not only help the households in making them aware of the heat pump technology, but also sell heat pumps. The latter will not be modelled explicitly, since the installers are not modelled as entities. The government interacts with the households through measures such as subsidies, regulation and taxes. Then there are the macro developments, which involves the remaining important variables that cannot be directly linked to the three actors or the heat pumps, but hold important factors such as the learning effect, energy prices and the CO_2 emissions per m^3 or kWh.

4.3 Conclusion

As in all chapters' conclusions, the research question is recalled: *"What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using Agent Based Modelling?"* This chapter provides the system description for the ABM. Thereby it does not only place the financial incentives, it also provides the elements of the model, the agents, the environment and the interaction. Based on the system, the next step to a more detailed description of the model can be made in chapter 5.

The agents of the model are households, as they have to make the decisions about adopting heat pumps. They do this by calculating 8 factors: Savings, Energy-label stimulation, social influence, investment costs, payback time, income-factor, the environmental benefit and the hassle factor. The other relevant actors, the installers and government, are part of the environment. The interactions between the households themselves are the word-of-mouth. Households interact with installers by retrieving advice, are influenced by governments by subsidies and other stimulating measures, and they adopt heat pumps. The time frame is set from the year 2017 to 2050, with a time step of 1 year, which means the model will run for 33 years.

5

The process of the heat pump adaption model

In the previous chapter, the systems entities and interactions are described. Before these are described in more detail, first the process of the model is presented. The chapter starts with the timeframe and the time step in 5.1, followed by the high-level process of the model in 5.2, which provides the steps of the model from the initialization (or setup) to the end of a run. In 5.3 the model narrative of two stages of the model is presented: the conditional checks and the decision module. The model narrative is a chronological description of all events in a single time step.

5.1 Time frame and time step

The time frame follows from the ambition of the Dutch government to be CO_2 neutral by 2050, as is published in the *Energie Agenda 2016* (Ministry of Economic Affairs, 2016a). Therefore, the model will run until 2050. The starting year will be 2017 It is assumed that households don't decide often on replacing their heating system, which is why the time step is 1 year. This is also because there aren't any variables that have units smaller than 1 year. In total, there will thus by 33 time steps.

5.2 High-level process of the model

In Figure 13 the high-level process in the model can be seen, which represents the basic structure of the model. First the model is initialized, which gives the households and the environment their state variables. This will be described in 6.2.

After initialization, the first procedure in the model is the update of the environment, which updates variables such as the gas price and learning curve effects. The household's first action after initialization is going through three conditional checks. First they check if they have a reason to adopt. The reason represents the moment for a household to consider a new heating system, which is based on the lifetime of their gas boiler, and the times a household moves. Second check is the awareness, if a household is simply not aware of heat pumps; there is no chance that they will adopt. This is followed by the decision to either lease or buy a heat pump. After the conditional checks, the decision module starts. First the intention is calculated for each heat pump type, based on the 8 decision factors described in 4.1, which is also where the TPB comes into play. The households then check their resources and adopt the preferred heat pump if they want to. The heat pump statistics are update, the results of this time step are reported and the model moves to the next year, as the time frame is 33 years, this happens 33 times.

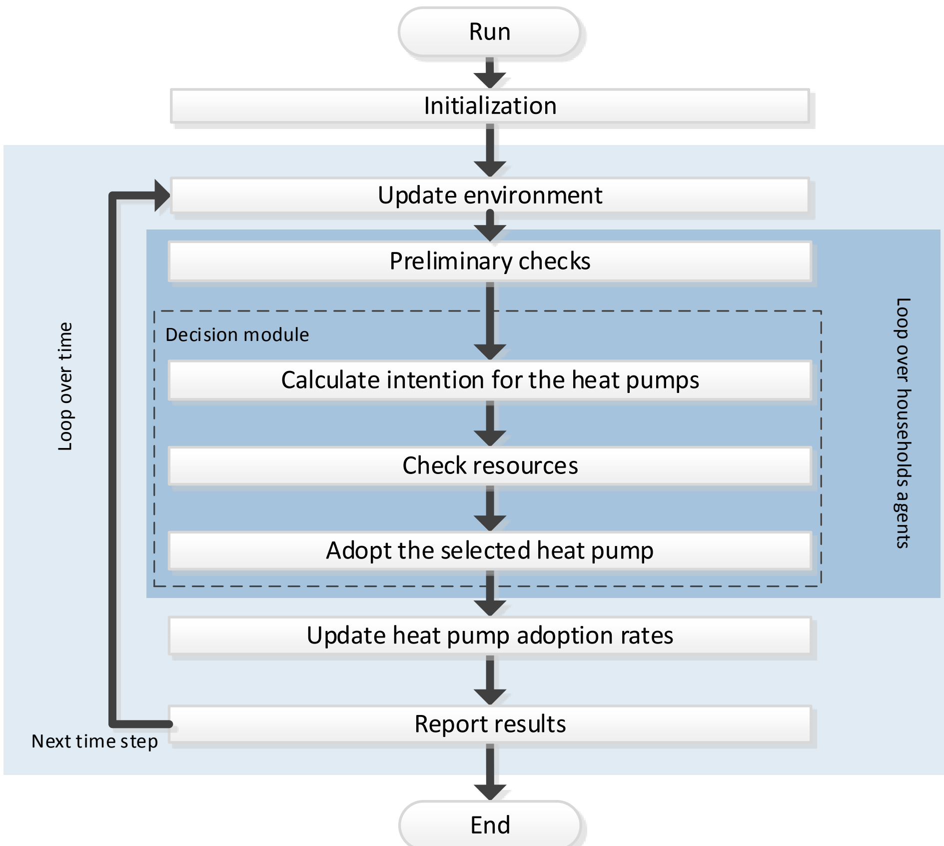


Figure 13: High-level process of the model

5.3 Low level process: Conditional checks and the decision module

Contrary to to the high-level process in 5.1, the low-level processes give a more detailed description of what happens in the model. Of the steps in Figure 13, only the processes in the darker (blue) colour framework, with *loop over household's agents* next to it are worked out in detail here. The low level process thus shows what takes place in one time step.

5.3.1 What the environment does in one time-step

The only thing the environment does is update variables in the *Update Environment* step and update the heat pump adoption rates after all households have exited the decision module. The narrative for the environment is therefore rather short.

Firstly, the environment updates all global variables that are dynamic, such as the gas price, the electricity price, the amount of CO_2 per kWh depending on the share of renewables in the electricity generation, the gas supply and network costs and the COP. Learning effects are calculated leading to lower investment costs and better performance of heat pumps. At the end of the step the environment updates the statistics of the total cumulative heat pumps installed, as well as adoption rates per year, the adoption rate per heat pump type and the adoption per household group.

5.3.2 Conditional checks

The first action a household takes in the model after initialization is checking whether it already has a heat pump installed. If so, it will skip all remaining procedures and remain idle for the rest of the time step. The subsequent step is the reason. It will check if the households needs to replace its gas boiler or faces a large scale renovation. If this is not true, the household remains idle for the rest of the time step. If it is true, it will continue by checking if it is aware of heat pumps. If not, the household will update its awareness by communicating with a peer of its social network, by checking (social-) media or by counselling the installers. The latter can only happen when the households have a reason, since that is the moment to consult an installer. The other two ways, media and social network, can happen every time-step, irrespectively whether the household has a reason or not. Then, dependent on the leasing possibility, the household will calculate whether it is better for him to lease or buy, for each heat pump type. If all these checks are passed, the household continues to the decision module. In Figure 14 the flowchart of the conditional checks is presented.

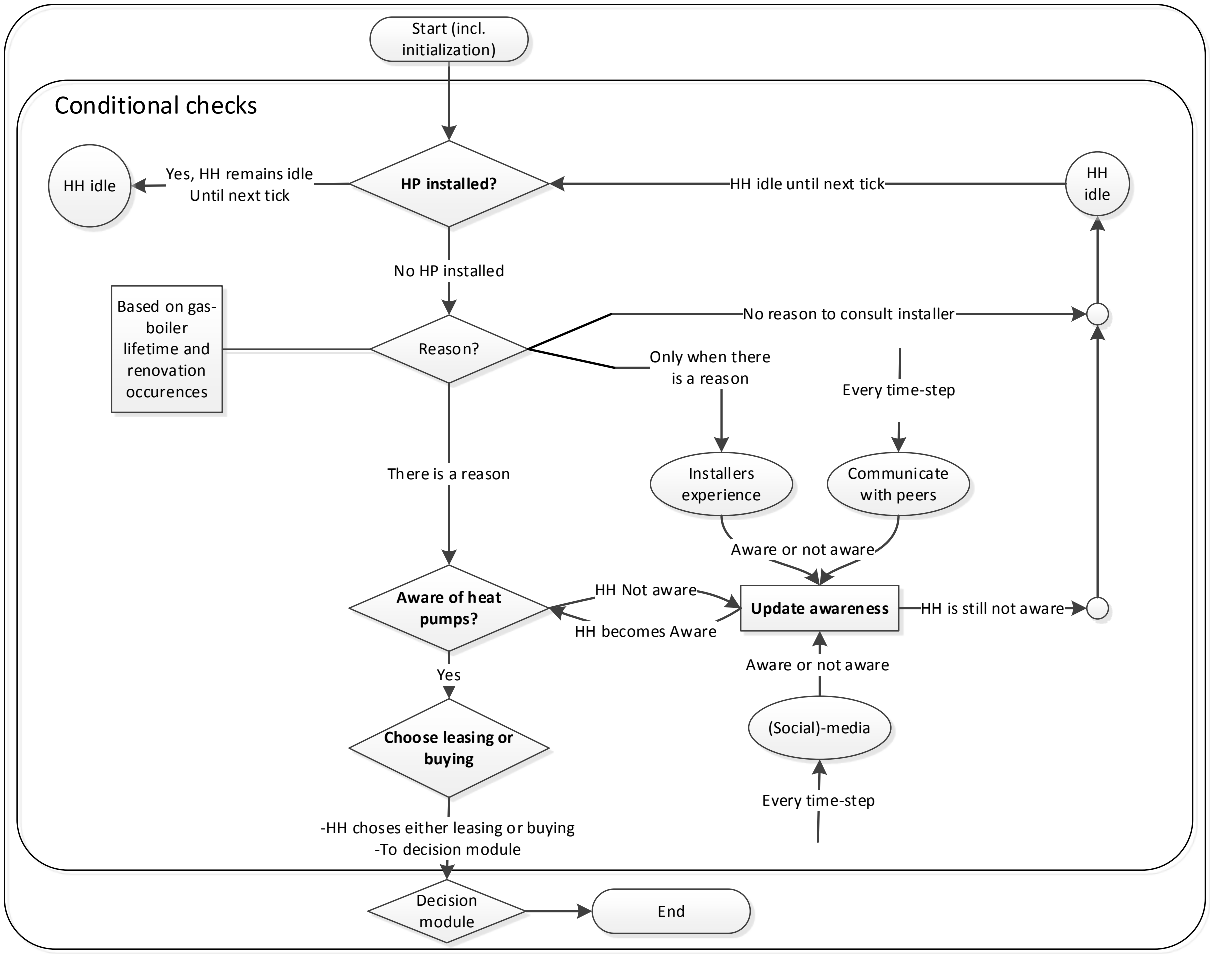


Figure 14: Flowchart of the conditional checks

5.3.3 Decision module

One of the household's outputs in the decision module is the intention to buy heat pumps. The intention value is the result of a calculation. As is described in Chapter 2, the TPB consists of three attributes: Attitude, Perceived behavioural control and the Social norm. These attributes are based on the 8 decision factors. Therefore the next step is to assign the decision factors to one of the three attributes.

Of the three attributes, the social norm is arguably the most straightforward. The social norm concerns the influence of the environment and the social pressure to perform or not perform a certain behaviour (Ajzen, 1991). Naturally, the social influence is part of this attribute. The E-label stimulation factor belongs to the social norm as well, as this is a factor that represents the pressure by the government to improve the household's energy-label.

The other two attributes leave more room for discussion. The attitude is about the evaluation towards the behaviour and whether the behaviour has desirable consequences or not. It is interpreted as the following: all factors that are part of the attitude should have some perceived result in the eyes of the households. Factors whereof households think have a consequence they can grasp, whether it is positive or negative. One of the most direct consequences households think about, are the costs. The payback time and savings are therefore strong indications of a consequence answering the questions: when do I have my money back or what costs are saved by using a heat pump instead of a gas boiler? And how much do I save per year if I would choose a heat pump? Following this logic, then why is the investment costs not a part of the attitude? With the investment costs is meant the total upfront cost a households has to pay for the entire heat pump package, the heat pump itself, insulation and low temperature heating. No matter how good the savings and the payback time is, the household still has to provide the upfront payment, and such a big investment may give households the feeling that it doesn't fit their budget. Now the definition of the PBC is: 'The perceived ease or difficulty of performing the behaviour' (Ajzen, 1991, p188). The higher a barrier is perceived by a household, the higher the perceived difficulty to perform the behaviour. As the investment cost can be interpreted as a barrier to adoption, it fits better with the PBC than with the attitude.

Another factor that concerns a certain consequence is the environmental benefit, as it gives an indication of how much the carbon footprint can be reduced, given that the household cares for the environment. The hassle factor is last factor belonging to the attitude, as households might think of all things that happen to their place with a heat pump, resulting in unwanted consequences. Besides the investment costs, the income is also part of the PBC, as a higher income gives households more possibilities.

<u>The process of the decision module</u>

If a household makes it through the conditional checks, it starts calculating the decision factors. This process can be found in Figure 15. As the payback time is based on the savings and investment costs, it is necessary that the last two are calculated first. The environmental benefit, payback time, investment cost, hassle factor and savings differ per heat pump type, whereas the social influence, income factor and E-label stimulation factor are the not dependent on the heat pump type. Based on the household's income, the income factor is calculated. The households also ask all households in its social network whether they have a heat pump, using these numbers the social influence is calculated. The hassle factor is checked, and if there are E-label requirements active, the households calculates the pressure. After all decision factors are calculated, the households can derive their attitude, PBC and social norm.

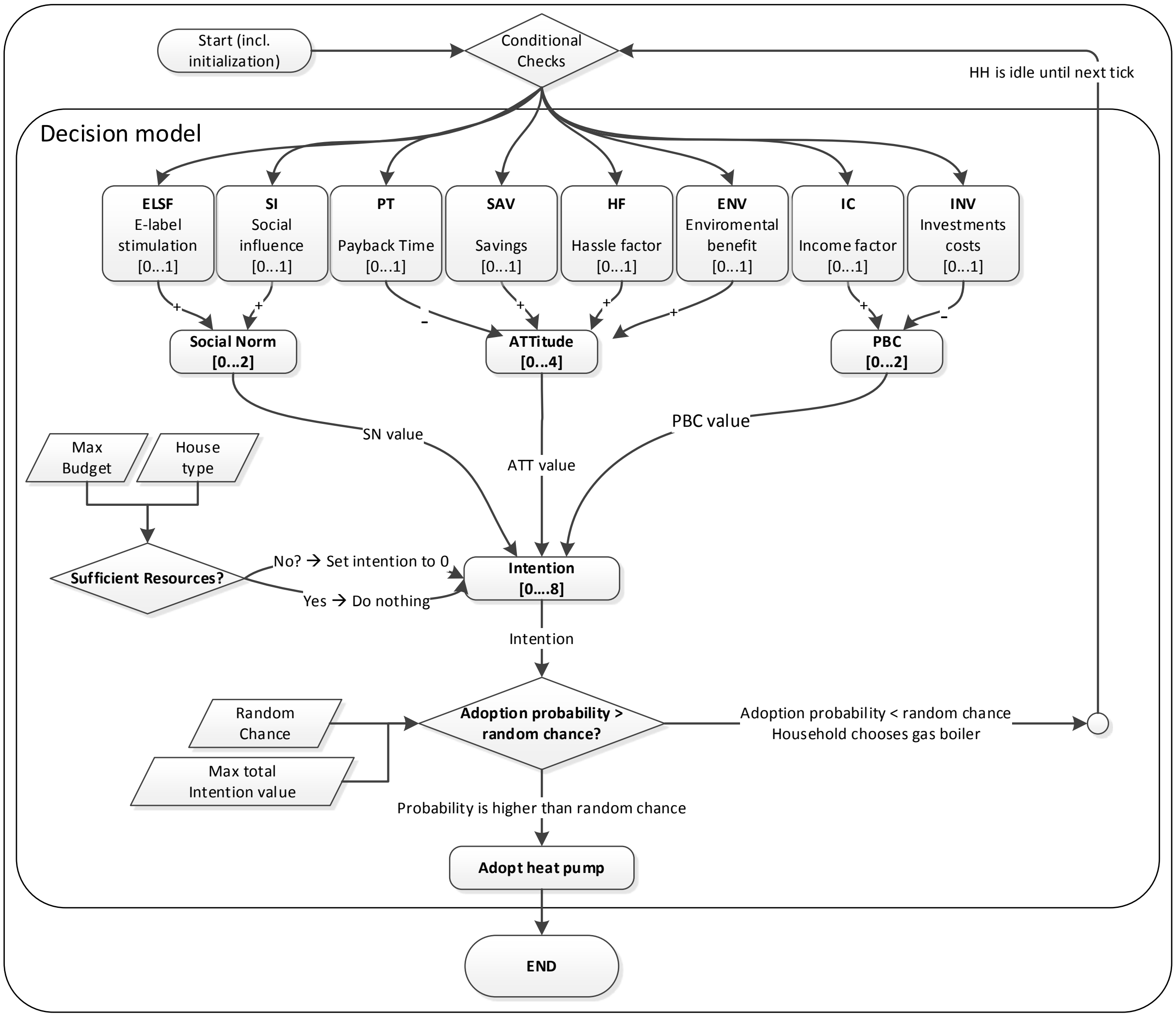


Figure 15: Flowchart of the decision module

Subsequently, the households multiply all decision factors with its associated weights. All factors are added, the hassle factor is subtracted, which leads to an intention for each heat pump to adopt. If the house type is not suitable for GSHP, or there are no sufficient resources, the household will not intent to adopt, which can be seen in the side step in Figure 15. Then a certain probability of adoption for all heat pump types is calculated, as well as the probability that the household doesn't adopt (i.e. installs a new gas boiler). The higher the intention, the higher the probability. Based on a random value, the household then make a choice. If the choice is for a heat pump, the household adopts, changes its corresponding variables.

5.4 Conclusion

Again, we look back at the research question and how this chapter helps answering it: *"What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using Agent Based Modelling?"* In the previous chapter we've seen what entities is part of the system. In this chapter it is shown how the entities and their characteristics act and are updated in the process of the model. Therefore it gives structure to the Agent Based Model.

The steps are as follows: after the model is initialized at the start, the first thing that happens during one time step is the update of the environmental variables such as the learning effect and CO_2 emission factor. Then the households come into play. They first go through the conditional checks: do they already have a heat pump, do they have a reason, and are they aware and do they want to buy or lease. Once these checks are completed for the households that satisfy the conditional checks, the decision factors are calculated in the decision module. Based on the intentions, the household chooses whether a heat pump is adopted or that a gas boiler is still preferred. If one of these conditions is not met, the household adopts a gas boiler. In the model, this essentially means that the household remains idle. Lastly, the results are calculated. The 8 decision factors are divided over the TPB attributes. Social influence and E-label stimulation factor belong to the Social norm, the investment costs and income factor to the perceived behavioural control and the savings, payback time, environmental benefit and hassle factor belong to the Attitude. In the following chapter, all steps of this chapter are formalized into more detail.

6

The conceptual model of heat pump diffusion

The next step in Part II is to formalize the system elements and the process into detailed descriptions that can be implemented into the model. This means that each variable in the model will be described. The structure is similar to that of chapter 5; although first a small description of the implementation in Netlogo is give in 6.1. Thereafter the initialization of all variables is explained in 6.2, for both households and the environment. Subsequently, the conditional checks are described in 6.3, followed by the decision module in 6.4. Then chapter continues with a description of the weights per decision factor for all the household groups in 6.5 and the stochasticity in the model in 6.6. Then some additional assumptions made are described. Finally, the verification is described in 6.8 and the conclusion of this chapter is provided in 6.9.

6.1 The software used for ABM: Netlogo

The software used for the implementation of the model is Netlogo (v6.0.1). Netlogo is a free program with a fairly simple programming syntax based on Java. Within Netlogo the possible agents are patches, turtles, links and the observer. The turtles are the agents that can move around in the world, and are typically modelled as the main entities, such as households in the model. Patches have coordinates, and the number is determined by the size of the interface. Links are agents that do not have coordinates and are connected between two agents. The observer can be seen as the manager of the model, as it gives instructions to other agents. Each agent can have variables. Important types of variables are the *global variables*. Which are general variables that are the same for every agent. The variables from the environment of the system (Chapter 4) are all modelled as global variables. They can be seen as properties of the observer. The government and installers are not modelled as separate agents, but as part of the environment. All the variables belonging to these actors are thus global variables.

6.2 Initialization of the households and the environment

6.2.1 Initialization of the households

In this paragraph, it is described how many households are in the model, how they are derived from the dataset, the variables describing the properties of these households and how these variables are initialized. As some of the variables are dynamic, thus changing in time, it is also explained how these variables change over time.

6.2.1.1 The number of households in the model

Ideally, all households in the Liander region are included into the model. This way, per region it can be directly seen where the heat pumps are adopted. However, running a model of 1.6 million households would make the simulation time too long to be able to run experiments. A representative sample of 3000 households is chosen instead. Also, at DSO Alliander, the effect per region is calculated in the *ANDES* model (see 2.2.1). For answering the research question, a representative sample of the households in the Alliander region is sufficient. A representative set of all households in the Netherlands could also be used, however, the dataset available (EDM) has only the households in the Liander Region. This means that all conclusions derived from this thesis all only valid for the region of Alliander. Another reason for this is seen when comparing the region of another DSO Stedin with the region of Liander. Stedin is located in and closely around the Randstad, which has many urban regions. Liander's region has more rural areas. It would thus be questionable if the conclusions from this research are also valid for other regions.

The EDM dataset

The dataset containing the households was randomly selected from the EDM database. Before this selection was made, a filter on household properties was applied. As rented houses are outside the scope, these are the first to be filtered out. Another EDM variable describes whether a household is connected to a heat grid. It is assumed that the chance that these households will switch to a heat pump is small. Therefore, all these households are also excluded from the dataset by filtering.

A sample was randomly made from the around 1.6 million households. To check if the sample was representative for the EDM dataset the averages and standard deviation of EDM and the sample was compared. No major differences were found, thus the sample sufficiently represents the EDM dataset. The number can be found in B.1.

6.2.1.2 The households variables

Table 6 below presents an overview of the variables that reflect the properties of the households. The table has been divided into sections. Heterogeneous variables are different for all households, where homogeneous are the same. Static variables remain the same for the whole simulation, where dynamic variables change. At the far right end of the column one can see where the variable is described. For the dynamic variables, it will also be discussed how they change during a model run. In the remainder of the chapter, *i* represents the households, where *j* are the different heat pump types. In Table 6, when the range has a value of X, this means that the value is not fixed for each household.

Table 6: Overview of the household's variables

Variable	Unit	Range	Static/ dynamic	Source	Paragraph
Heterogeneous variables from EDM					
Income	Coded	[1-6]	Static	EDM	6.2.1.3
Gas usage	m^3/year	[300-5000]	Static	EDM	6.2.1.4
Household group	Coded	[1-14]	Static	EDM and Motivaction	6.2.1.5
House type	Coded	[1-2]	Static	EDM	6.2.1.6
Energy label	Coded	[1-10]	Dynamic	EDM	6.2.1.7
Other heterogeneous variables					
Social Network (SNW)	Num. HHs	[0…X]	Static	Random	6.2.1.8
Maximum budget	Euro	[0-100.000]	Static	Based on income	6.2.1.9
Media-factor	-	[0.05-0.20]	Static	Based on HHgroup	6.2.1.10
Awareness?	Boolean	True/false	Dynamic	Own assumptions	6.2.1.11
Awareness THLD	-	[1-5]	Static	Own assumption	6.2.1.11
Heat pump?	Boolean	True/false	Dynamic	(CBS, 2017c)	6.2.1.12
Reason counter	Year	[0-10]	Dynamic	Own assumptions	6.2.1.13
Insulation costs	Euro	[0-12000]	Dynamic	Based on energy label	6.2.1.14
LTH-costs	Euro	[0-X]	Static	Based on gas-usage	6.2.1.15

Initial HP costs	Euro	[0-X]	Static	Based on gas-usage	6.2.1.16
Homogeneous variables					
Upfront payment when leasing	%	20	Static	Own assumption	6.2.1.17
HP electric backup	%	3	Static	Beta-factor	6.2.1.18
HP gas backup	%	25	Static	Own assumptions	6.2.1.18
Gas supply and network costs	Euro	[200-X]	Dynamic	Multiple	6.2.1.18
Gas supply and network increase factor	%	2	Static	Own assumptions	6.2.1.19

The variables derived from EDM In the EDM dataset characteristics of the Dutch households in the Liander region can be found. This concerns subjects on demographics, energy, financial and behaviour. Remaining variables not coming from EDM are based on assumptions and other sources as is mentioned in the Table 6.

The variables from the EDM database used in our model are the *income, gas usage per year, household group, house type,* and *energy label*. All variables of EDM have coded nominal and ordinal values, not the real values. For all variables, a 0 means that it is unknown. Households that have a 0 in one of the 5 EDM variables are excluded from the dataset.

6.2.1.3 Income

In EDM the income has a minimum value of 0 and a maximum of 6 and is based on the modal income. The higher the number, the higher the income. A value of 0 in the EDM dataset means that no data is available for that household. These households are excluded from the dataset, and therefore the values range from 1 to 6. The groups are assigned as follows:

Table 7: Income values in the model

Value	Income
1	Minimum
2	Below modal
3	Modal
4	1.5 times modal
5	2 times modal
6	2.5 times modal or higher

6.2.1.4 Gas usage

The gas usage in EDM ranges from 1 to 14 (after excluding the unknown 0), where 1 is equal to a gas usage below 600 m^3 per year, and 14 is equal to 2.400 m^3 or more per year. In the model actual gas usage is needed instead of the numbers from 1 to 14, therefore these are converted to plausible numbers corresponding to the ranges given by EDM. This is done by randomly assigning a number between the ranges given below. The assumption is made that the households with a gas usage 1 in EDM have a minimum use of 300 m^3 per year, where the maximum for the highest gas usagers is 5000 m^3 per year.

Table 8: Gas usages based on EDM data

Number in EDM	Range given by EDM In m^3 per year	Value in Model in m^3 per year
1	Below 600	Between 300 – 600
2	600 – 700	Between range EDM
3	700 – 800	Between range EDM
4	800 – 900	Between range EDM
5	900 – 1000	Between range EDM
6	1000 – 1100	Between range EDM
7	1100 – 1200	Between range EDM
8	1200 – 1300	Between range EDM
9	1300 – 1400	Between range EDM
10	1400 – 1500	Between range EDM
11	1500 – 1700	Between range EDM
12	1700 – 2000	Between range EDM
13	2000 – 2400	Between range EDM
14	2400 and more	Between 2400 – 5000

6.2.1.5 Household groups

EDM also provides the mentality groups to which households can belong. There are 8 mentality types, however, in this study, the household groups are used based on a report by Motivaction (Randsdorp & Schoemaker, 2014), as is described in 3.2.6. In that report, the mentalities are combined to form the four household groups; therefore they are merged as follows

Table 9: The household groups based on the mentality

Name	Mentality groups	Number
Unaware energy users	Modern mainstream + Convenience oriented	1

Pragmatic comfort seekers	New conservatives + Social climbers	2
Environmentally aware Improvers	Cosmopolitans, post materialists, post-modern hedonists	3
Faithfull environmentalists	Traditionals	4

6.2.1.6 House type

House types in EDM are divided into 15 types. It is assumed that all house types are suitable for ASHP or HHPs. For GSHP, this is not the case. Naturally, for apartments and flats without a garden, a ground source heat pump is impossible. The households thus either have a value 1 or 2.

Table 10: House types in EDM and house types in the model

Number in EDM	House type	Value in Model
1	Detached house	1
2	Semidetached	1
3	Terraced house	1
4	Corner house	1
5	Flat / apartment	2
7	Maisonette	2
8	Mansion / canal house	1
9	Farm / Horticulture	1
10	Student house	1
11	Independent retirement home	1
12	Caravan / houseboat	1
13	Business / practice house	1
14	Other housing type	1
15	Non-dwelling	1

6.2.1.7 Energy label and the energy label decrease factor

Energy labels in the Netherlands range from G (worst), to A++ (best). In the EDM dataset, A, A+ and A++ are given the same coding. This is directly copied into the model. Thus a 1 being the best energy label and 7 the worst. The energy label will be a dynamic variable. Not only has the amount of insulation measures drastically increased from 1982 to 2012 (CLO, 2015), also the government's policy is aiming to invest on large scale on insulation measures in the future (Ministry of Economic Affairs, 2016a). The latter is not surprising, as improving the insulation levels can drastically decrease the energy use, and thereby also the CO2 emissions (PBL, 2014). Based on the a report by the CLO (2015), it was calculated that on average the increase of insulation measures per year is 1.72 percent. Translated to the model this means that randomly, every year 1.72 percent of all households (without E-label A or higher) will upgrade their energy-label. As a low number means a better energy label, the E-label thus decreases, hence the name *E-label decrease factor*. The calculation of this percentage can be found in B.3.

Table 11: The possible energy-labels in the model and the E-label increase factor

Energy Label	Value in EDM	Value in Model
A / A+ / A++	1	1
B	2	2
C	3	3
D	4	4
E	5	5
F	6	6
G	7	7
E-label decrease factor		1.72

6.2.1.8 Constructing the social, scale-free network

Households base their decisions partly on their social network. As is described in 3.4.1, the scale-free network is a good representation of actual network. It is implemented based on the preferential attachment mechanism by Barabási & Albert (1999). Preferential attachment means that the more connections a node in a social network a household has (thus the higher the degree), the higher the probability that the next node in line connects to the node. The result is a network with a few heavy nodes (i.e. with a high degree) and numerous other nodes with smaller degrees. The probability is calculated as follows:

$$P_i = \frac{k_i}{\sum_j k_j} \qquad \text{Eq. (6)}$$

In which k_i is the degree of the node, where the denominator is the sum of the degrees of all other nodes. In the model[6], firstly the initial connected network is constructed, based on a specified number. This number is set on 25. This means that the initially connected network consists of 25 households. These 25 households are added to the *social-network-longlist.* The next household (the 26th) adds a connection randomly to one of the households from the *social-network-longlist*. Subsequently the household adds itself and the other household, to whom a connection is made to the *social-network-longlist.* All following households do the same, making the list longer, with the possibility that one household appears on the *social-network-longlist* multiple times, thereby

[6] Netlogo code for the social network thanks to Dr.ir. E.J.L. Chappin

increasing the preferential attachment of that household. Each time a household connects to another household; both households are added to the list. k_i of a household is the number of times it occurs on the *social-network-longlist*, and $\sum_j k_j$ contains the rest of the list. This way the more a household occurs on the *social-network-longlist* the higher the chances for another connection.

6.2.1.9 Maximum budget of a household

As heat pumps are a costly investment, not all households may have the resources to buy one. Therefore, every household has a maximum investment value which follows directly from the income. Thereby the assumption in the model is made that the income is a strong indicator for the resources available. The highest income group can thus buy everything under 100.000 euros, which means they can buy every heat pump priced in the model. The values are as follows.

Table 12: The maximum budget per income group

Income	Description	Maximum investment in euros
1	Minimum	0
2	Below Modal	5.000
3	Modal	10.000
4	1,5 × modal	20.000
5	2 × modal	30.000
6	2,5 × modal and higher	100.000

6.2.1.10 Media-factor

This factor is based on own assumptions and represents both conventional media as social media, through which households can become aware of heat pumps. The more environmentally friendly a household, the higher the factor. For this variable the same name is used as those for mentality groups.

Table 13: The media factor per household group

Name	Media factor	Percent of total in model
Unaware energy users	0.05	25%
Pragmatic comfort seekers	0.10	23%
Faithfull environmentalists	0.15	43%
Environmentally aware improvers	0.20	9%

6.2.1.11 The awareness of households

The initial awareness of households is based on the household group. The more environmentally friendly a household is, the higher the chance that it is aware at the beginning. The media factor described above is used here. Which means that the media factor gives the percentage of households of that household group that are aware at the start of a run. The households that are not initially aware can become aware during a simulation. This is true once they pass a threshold, which is the$AwarenessThreshold$. This value is assumed to be set randomly on a value between 1 and 5. The working of the awareness procedure in the model is explained in 6.3.

6.2.1.12 Initial heat pump ownership in 2017

To assign households with heat pumps in the initialization, data is needed about the whereabouts of heat pumps in the Netherlands. Unfortunately, this data is not available in EDM or through other known sources on the web or at Alliander. What we do know is the total number of heat pumps in the Netherlands for every year for households. As of end 2016, around 180.000 residential heat pumps are installed in the Netherlands (CBS, 2017c). As the ASHP statistics from CBS also include hybrid heat pumps, it is assumed that half of the ASHP are hybrid heat pumps and the other pure ASHP with no gas boiler. The next limitation that arises is that this number says nothing about the number of heat pumps in owned houses, but only the total for rented and owned houses. Therefore it is required to take the total number of households in the Netherlands in 2017 into account, which amounted to 7.7 million. According to these statistics, 2.3% of all households in the Netherlands have a heat pump installed. It is assumed that the same statistic is true for owned houses. This means that with a total number of 3000 in the model, initially 70 households have a heat pump.

Another difficulty with the initial number of heat pumps installed besides that is also includes rented houses, is that is also doesn't specify what amount of the heat pumps where installed when the house was newly build at that time. It might be the case that the majority of installed heat pumps were incorporated in newly build houses, since it is easier to include them in the design of a house when it is not build yet. The reason that this number is still being used is because it is simply the only hard number that is available.

6.2.1.13 Reason-counter

The reason-counter of households represents not only the age of the gas-boiler and the possibility that it could break down (elapsed part of the lifetime), but also other occurrences when a household could decide to change the heating system, such as a renovation. The average lifetime of gas-boiler is around 15 years. Statistics on large scale renovations are not available, however, a Dutch person on average moves once every 10 years (Appendix A.1). Assuming most large scale renovations occur after a move; this thus increases the chance that a household chooses for another heating system. The initial range of the reason-counter has been set from 1 to 10. As there is no data available in the EDM data for this variable, the reason-counter will be randomly assigned to each household between 1 and 10 years. The working of the reason can be found in 6.3.

6.2.1.14 Insulation costs

The insulation value of houses is normally expressed in the R_c value[7]. However, this data is not available, and therefore it is assumed that the energy label ($ELABEL_i$) is a sufficient representation of the insulation value of a house. It is assumed that houses with the best energy label have perfect insulation, whereas the houses with the worst energy-label have no insulation measures whatsoever. The costs are calculated as follows. As the insulation costs are dependent on the energy label, it is a dynamic variable. The estimation is made that improving the E-label with 1 step, costs around €2.000. See B.4 for more information.

$$CostInsulation_i = (7 - ELABEL_i) \cdot €2000 \qquad \text{Eq. (7)}$$

6.2.1.15 Low Temperature Heating (LTH) costs

For LTH it is assumed that generally, existing households will not replace their current heating release systems with wall heating or floor heating. These types of low temperature heating involve a lot of hassle and extra costs, as floors and walls need to be opened up for installation. Therefore, it is assumed that all households will choose for a low temperature (LT) radiator. Other names for a LT-radiator are LT-convection or low-H_2O-radiator. These types of radiators are suited to be connected to heat pumps. Another key assumption is that there is no LTH required for a HHP. Thus the $CostLTH_i$ will only be used for ASHP and GSHP calculations.

The LTH costs are based on four basic LT-radiator types: *Strada, Tempo Wand, Linea Plus Wand and Maxi Wand* of supplier *Jaga* (at www.jagapro.nl) it was calculated that the median costs per Watt are €0.77. This puts the average costs per m^3 natural gas at €4,80, when assuming a needed power of 10 kW when the gas usage is 1600 m^3 per year. A further explanation can be found in B.4, from which the following equation is extracted:

$$CostLTH_i = GU_i \cdot 4.80 \qquad \text{Eq. (8)}$$

In which $CostLTH_i$ is the total costs of the low temperature heating and GU_i is the yearly gas usage.

[7] The Rc value represents the heat resistance in certain part of a house. The higher the Rc value, the less heat is lost.

6.2.1.16 Initial heat pump costs

Before it is explained how the costs in the model are calculated, let's take a look at how the dimensioning of the heat pump is normally calculated in the industry. There are multiple ways of calculating the dimensions of a heat pump. The first two calculations are based on Bosch/Nefit Enviline data for their heat pumps (BOSCH, n.d.). These are used for rough estimations of the heat pump capacity for non-hybrid heat pumps (ASHP and GSHP in this thesis). For a detailed dimensioning of a heat pump, a heat loss or transmission calculation is used.

Calculation 1: Calculate the total power of the heat pump based on the gas usage

This method is generally used for houses build before 2000. One takes the gas usage, subtracts the gas needed for heating the tap-water and cooking, and then reads the power needed for the heat pump from a diagram. A gas usage of 2000 m³ is equal to a capacity of 10 kW, as is shown in Figure 16.

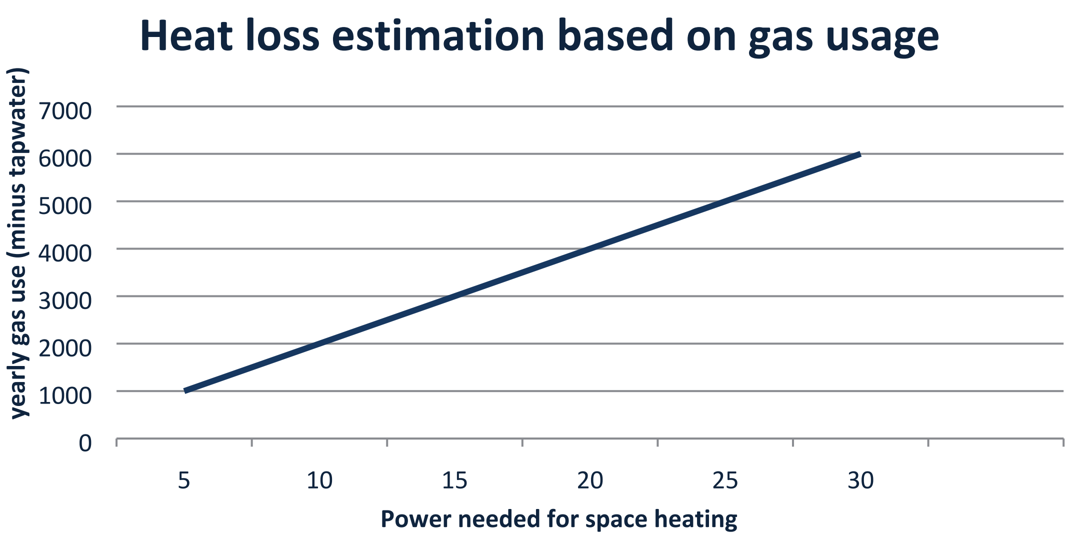


Figure 16: Diagram adopted from producer Bosch (BOSCH, n.d.) concerning their product line Nefit Enviline II

Calculation 2: Calculate the total power of the heat pump based on key figures

Opposed to the first calculation, this method is generally for houses build after the year 2000. These key figures are estimated for houses with high insulation values, which are naturally mostly recent build houses. The total surface of all heated spaces of the house is calculated, which is then multiplied by heat per m² in W/m² to get the heat demand. For example, a detached (extremely well isolated) house build in 2017 needs on average 54 W/m² (BOSCH, n.d.). Suppose it has a to be heated surface of 185 m², this means that the total heat demand is around 10 kW. The capacity of the heat pump in this case would also amount to around 10 kW.

Calculation 3: Calculate the total power based on heat loss calculations

The first step is to calculate the total heat loss of a house, based on industry standards by ISSO (ISSO, 2005). A common name for this is a *transmission calculation.* The total heat loss in a house needs to be equal to the heat supplied by the heat pump, and gives an indication of the total power needed for space heating for the entire house. Such calculations are executed by calculating the heat flux through a structure, given by Eq. (9). If one does this for all structures (roof, walls, glass) of a house, the total heat loss in Watts can be estimated.

$$Q_h = U \cdot A \cdot \Delta T \qquad \text{Eq. (9)}$$

Where Q_h is the heat flux, or heat loss through the structure, U is the U-value in $\frac{W}{m^2 \cdot K}$ A is the surface in m² of the structure and ΔT is the difference in temperature between the two sides of the structure. A common procedure is to take the R-value instead of the U-value, which is given by Eq. (10). The R-value is heat resistance through a surface per square meter and per degree temperature difference in $\frac{m^2 \cdot K}{W}$. The heat flux calculation through a structure is than equal to Eq. (11).

$$R = \frac{1}{U} \qquad \text{Eq. (10)}$$

$$Q_h = \frac{\Delta \mathrm{T} \cdot \mathrm{A}}{R} \qquad \text{Eq. (11)}$$

Where the variables Q_h,ΔT and A are the same as described above. Both U and R values for the different structures are recorded in industry standards and can be acquired at ISSO.nl. Calculating the heat flux once for every structure is not sufficient, as one needs to know the heat flux during the entire year with different temperatures. A heat pumps capacity based on measurements in a relatively warm period would not be capable of providing heat during winter. Therefore, one needs to make multiple calculations for temperature differences during a year. If the interval of the calculations is one hour, thus one measurement each hour in a year leads to 8760 (24 · 365) points in a year. This is useful because now the maximum needed total heat loss of a house is known, which is called $Q_h Max$ in this thesis (the highest total heat flux of a house during one hour in a year). During this time, where the heat loss is the highest, the heating system in use has to provide the most heat, which thus gives an indication of the capacity of the heating system. It is not common however, that a heat pumps capacity is dimensioned equal to this maximum heat loss. Instead, a so-called *beta-factor* is used. The beta factor provides the relation between the portion of heat that a heat pump provides when the dimension is a certain percentage of $Q_h Max$, as can be seen in Figure 17. Just like the U and R-values, this relation can be acquired at ISSO.nl[8]. This relation says that if the dimension a heat pump is 80% of $Q_h Max$, that 97% of the yearly heat demand is provided by the heat pump. The consequence is a smaller and thus cheaper heat pump, and the need for a small back-up heater during the days when the heat demand is highest, which is the other 3%. This is typically a small electric resistance heater which is incorporated in the heat pump.

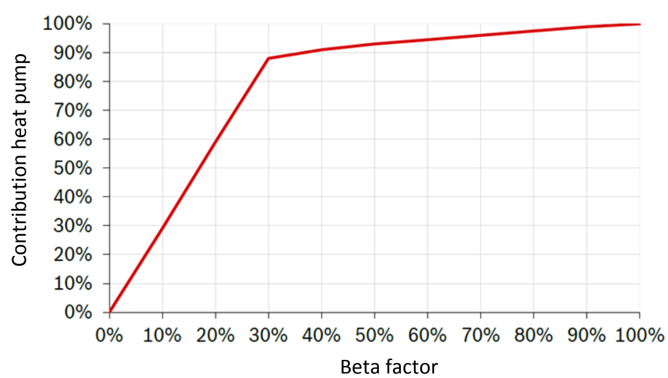


Figure 17: Relation between the beta factor and the contribution of the total het supply. Adopted from (BOSCH, n.d.)

The calculation of the heat pump costs in the models

So, three methods of calculation the total power of a heat pump have been provided. None of these however, will be implemented in the model. In the model, the power of the heat pump would only function as an intermediate step to estimate the total costs. The total power of a heat pump should thus lead to a certain cost. For this, market research is needed. There are many heat pumps on the market, and unfortunately, market research on all these heat pumps and their corresponding costs is too time consuming for this thesis. So although it is possible to calculate the power of heat pumps for each household based on either their gas usage, or surface (although an accurate transmission calculation would be too comprehensive for the model), this cannot be accurately matched to certain cost. It is thus difficult to implement these calculations in the model. Therefore another way of calculation is chosen.

[8] https://kennisbank.isso.nl/docs/publicatie/72/2014

From multiple Dutch sources the lower and upper bound of the heat pump costs were retrieved. The average upper and lower bound were calculated and rounded (0). The results are the following upper and lower bounds for the ASHPS, GSHP and HHP.

Table 14 Lower and upper bounds of the heat pump costs, based on 0, and the bound of the gas usage for the linear regression

Type	Lower bound	Upper bound
Gas Boiler	€700,-	€2.500,-
HHP	€4.500,-	€7.000,-
ASHP	€6.500,-	€11.500,-
GSAHP	€11.500,-	€20.500,-
Yearly gas usage	300 m^3	5000 m^3

The costs for a heat pump are still based on the gas usage just as in calculation type 1, only in a different way. The minimum and maximum bounds of the gas usage, which are 300 and 5000 m^3 respectively (see Table 14). These bounds are matched to the minimum and maximum of the heat pump costs. The costs for the lower and upper bound gas usages can be read from Table 14 . From these bounds, a linear function can be derived. Through linear regression the initial costs per heat pump type are found to be:

$$InitialCostHybrid_i = 0.53 \cdot GU_i + 4340 \quad \text{Eq. (12)}$$

$$InitialCostASHP_i = 1.06 \cdot GU_i + 6168 \quad \text{Eq. (13)}$$

$$InitialCostGSHP_i = 1.915 \cdot GU_i + 10926 \quad \text{Eq. (14)}$$

Where GU_i is the yearly gas usage of a household. Logically, the heat pump costs are dynamic over the timeframe. However, the calculation of the initial costs is the same for the whole period. The costs of heat pumps may change due to the learning effects, which is discussed in 6.2.2.5.

6.2.1.17 Upfront payment when leasing

One of the advantages of leasing opposed to buying is the lower upfront costs. There are numerous leasing constructions available. In this thesis however, the main interest is seeing the effect of the lower upfront costs. Other aspects of leasing (such as risks) are left out of the scope. Therefore, a certain percentage is estimated for the upfront cost called the $LeaseFactor$. In the model, the $LeaseFactor$ is assumed to be 0.20. Which means that when a household wants to lease, the upfront cost amount to 20%. For simplicity reasons, the effect on leasing on the total investment through interest rates is not taken into account.

6.2.1.18 The back-up heaters

In the model, two types of back-up heaters are present. The first are the small electric resistance heaters that are discussed in the previous paragraph. The HHPs however, don't use an electric resistance heater, but a gas-boiler. For calculating factors as the payback time, savings and environmental benefit, it is necessary to know how much of the total heat demand the back-up heaters provide. The previous paragraph already described the beta factor, which means the electric resistance heater provides 3 percent of the total heat demand. For the gas-boiler of the HHP system, this number is different. HHPs are generally smaller in power, which means the gas boiler takes up a larger share of the heat provision than 3 percent. HHPs work together with gas boilers. Normally the heat pump does most of the work, except for when the temperature drops below a certain level or when a lot of hot tap water is needed. In the model, it is assumed that the gas boiler provides 25% of the heat in total. So $BackUpElectric = 0.03$ for ASHPs and GSHPs, and $BackUpElectric = 0$ for HHPs. $BackUpGas = 0$ for ASHP and GSHP, and $BackUpGas = 0.25$ for HHPs

6.2.1.19 Network costs

The network costs consist of the network costs by the DSO plus a charge by energy suppliers called the *vastrecht levering.* Together these costs were around 200 euros per year on average over the past years (B.9), which is the initial value. As is it likely that less gas will be used over the 40 year model run, and that it will be encouraged to change to another energy source, the network costs will increase for every household every year based on a growth rate of 2%, based on the average growth of the consumer price index (see B.8)

$$CostNetwork(t) = 200 \cdot (1 + 0.02)^{(t - t_0)} \qquad \text{Eq. (15)}$$

Where $t - t_0$ is the number of years that have past, and $CostNetwork(t)$ are the total network costs at time t.

6.2.2 The environment

Next to the households, there are numerous exogenous factors that have to be setup at initialization. In the Table below gives an overview. For the dynamic variables, it will also be discussed how they change during a model run.

Table 15: Overview of the environments variables

Variable	Unit	Range	Static/ dynamic	Source	Paragraph
Electricity price	€/kWh	0.178	Static	(CBS, 2017a)	0
Gas price	€/m³	0.61	Dynamic	(CBS, 2017a)	0
Percent Subsidized	%	[0-100]	Static	Own assumptions	6.2.2.2
COP ASHP	-	3	Dynamic	(Mustafa Omer, 2008)	6.2.2.3
COP GSHP	-	4	Dynamic	(Brown & Stebnicki, 2011)	6.2.2.3
CO2 per kWh	$kgCO_2/kWh$	0.355	Dynamic	(Otten & Afman, 2015)	6.2.2.4
CO2 per m³	$kgCO_2/m^3$	1.8	Static		6.2.2.4
Learning rate (LR)	%	14	Static	(Weiss et al., 2008)	6.2.2.5

6.2.2.1 Gas and electricity prices

The gas cost starts at €0,61 per m³ in 2017 and will increase every year. To promote the shift away from gas the government is likely to increase the taxes on gas. Furthermore, gas supply will be more expensive due to the increased imports and scarcity. Biogas can fill up a small part of the gap left by gas, but biogas prices will also be significantly higher than normal gas costs (CE Delft, 2015). The gas price will develop as in Eq. (16).

$$CGAS(t) = 0.61 \cdot (1 + \Delta CGAS)^{(t - t_0)} \qquad \text{Eq. (16)}$$

In which $CGAS(t)$ is the gas cost at time t, 0.61 is the gas price in 2017, $\Delta CGAS$ is the gas price increase per year in %, which can be set in the model and $t - t_0$ is the number of years that have past.

The electricity price starts are €0,178 per kWh in 2017. It is assumed that the electricity increases with the average growth of the GDP in the Netherlands of 2%, thus the electricity price is as in Eq. (17).

$$CElec(t) = 0.178 \cdot (1 + 0.02)^{(t - t_0)} \qquad \text{Eq. (17)}$$

In which $CElec(t)$ is the electricity price at time t, 0.178 is the electricity price in 2017, 0.02 is the increase of electricity price every year (see B.8), and $t - t_0$ is the number of years that have past.

6.2.2.2 Percent subsidized

As the header above already suggests, the subsidy in the model will be in the form of a percentage of the total costs. The heat pump, insulation and LTH make up these total costs. The reason for a subsidy in percentages instead of a real value is that it is easier than implementing the ISDE subsidy construction. Also the ISDE somewhat works like a percentage, as the subsidy is higher as the capacity of the heat pump is larger. Furthermore, the ISDE (see 3.4.2.1) is only active in recent years, and the budgets are only released a year in advance. Therefore it is chosen to use the subsidy in the form of a percentage in our model. For simplicity reasons, it is chosen group all cost factors, instead of implementing the different subsidy types for each aspect (heat pump, insulation and LTH).

6.2.2.3 Initial COP values

The initial COP of GSHP, in 2017 will be 4, based on Mustafa Omer (2008). For ASHP, the COP is set on 3 based on Brown & Stebnicki (2011). As the hybrid heat pumps in this model are ASHP combined with a gas boiler, their COP is also set on 3.

6.2.2.4 Emissions per kWh and per m³ for electricity and gas

The initial CO_2 emission per kWh is 355 grams (Otten & Afman, 2015). The emission for natural gas is around 1.8 kg per m^3. As the electricity sector is also in a transition to renewables, the CO_2 emission factor for electricity is likely to decrease. In this thesis, the assumption is thus made that the electricity production in the Netherlands will continuously become *greener*. Therefore a certain improvement per year is introduced for the $CO_2PerkWh$. The assumption is made that the factor improves by 4% every year. Based on Eq. (18), this leads to a $CO_2PerkWh$ of 0.065 kg CO_2 per kWh in 2050. An improvement of 82% compared to 2017.

$$CO_2PerkWh = 0.355 \cdot (1 - 0.04)^{(t - t_0)} \qquad \text{Eq. (18)}$$

In which 0.355 is the starting value in 2017, 0.04 is the reduction in % every year and $t - t_0$ is the number of years that have past.

6.2.2.5 Learning rate and the development of the COP and heat pump costs

As is described in 3.3.2, learning or experience effects represent the experience of an industry. Through standardization, labour efficiency, specialization, better use of equipment, product redesign and innovation the cost and performance of a product can improve. The learning rate of energy supply technologies such as heat pumps typically range between 5% and 20% (Weiss et al., 2008). Weiss et al. (2008) estimated the learning rates for heat pumps and found that the learning rates for the performance (COP improvement) was around 13.8%, whereas the learning rates for costs were between 19 and 42%, based on a number of cases in Switzerland. However, the authors state that there was little data available, and thus the learning rates are very uncertain. Because there are no other numbers available, some assumptions have to be made.

Since heat pumps are a relatively mature technology, it is assumed that the learning rate of costs and performance does not fall in the highest ranges. The assumption is made that both learning rates are estimated to be 14%. An important assumption here is that the experience is valid for all heat pump types. Increasing experience (i.e. more adoption) in one of the heat pump types thus has the same influence on the experience on other types. Whether this holds true in reality is questionable, as installing multiple ASHP will not lead to experience in drilling and installing vertical pipes for GSHPs. A counter argument is a certain overlap in parts of the different heat pump types.

The learning rate is implemented based on Palmer, Sorda, & Madlener (2015). First the experience parameter $-b$ is calculated based the Learning Rate LR, which is thus set on 14% in Eq. (19). The result is an experience parameter of -0.218. Subsequently, the $ExperienceCurveParameter$ is calculated in Eq. (20). This is a parameter which is based on the growth of the total adoption rates and an experience parameter $-b$. In Eq. (21) and Eq. (22), this parameter is multiplied with the Initial costs and COP of a heat pump, which results in the heat pump costs and COP in the current year.

$$LR = 1 - 2^{-b} \rightarrow 0.14 = 1 - 2^{-b} \rightarrow -b = -0.218 \qquad \text{Eq. (19)}$$

$$ExperienceCurveParameter = \left(\frac{ACC(t)}{ACC(t_0)}\right)^{-b} \qquad \text{Eq. (20)}$$

$$CostHeatPump(t)_{ij} = InitialCostHeatPump_{ij} \cdot ExperienceCurveParameter \qquad \text{Eq. (21)}$$

$$COPHeatPump(t)_j = InitialCOPHeatPump_j \cdot ExperienceCurveParameter \qquad \text{Eq. (22)}$$

In which LR is the Learning Rate, $-b$ the experience parameter, $ACC(t)$ is accumulated number of heat pumps at time t, $ACC(t_0)$ is the total number of heat pumps in the base year 2017 $CostHeatPump(t)_{ij}$ is the cost of a pump at time t, $InitialCostHeatPump_{ij}$ is the cost of a heat pump in the base year, which follows from 6.2.1.16. $COPHeatpump(t)_j$ is the COP of a heat pump in a certain year, and $InitialCOPHeatPump_j$ are the starting COP values of the three heat pump types described in 6.2.2.3.

6.3 Formalizing the conditional checks

Is there a heat pump installed?

The first check a households performs in a time step is if the heat pump is installed. If that is the case, the household will remain idle for the rest of the time-step.

Is there a reason to adopt a heat pump?

As explained in 6.2.1.13, the households have a reason counter. The reason is a vital part in the model, as it determines the moment a household considers its options. When the gas-boiler is new, the chance of breakdown is low (2%), when it is 9, the chance is 24%, and older than 10 years, the chance is very high at 50%. The reason to adopt procedure works as follows.

$$ReasonCounter(RC)\begin{cases} RC < 9 \rightarrow P(Reason)_i = 0.02 \\ RC = 9 \rightarrow P(Reason)_i = 0.25 \\ RC > 9 \rightarrow P(Reason)_i = 0.5 \end{cases}$$

$$if\ FailureChance \geq P(Reason)_i \begin{cases} true \rightarrow Reason_i = \ true \\ false \rightarrow Reason_i = false, RC + 1 \end{cases}$$

The $FailureChance$ is a random value between 0 and 1, that is different each tick for each household. $P(Reason)$ is the chance that a household will have a reason to adopt. If the $FailureChance$ is higher than the $P(Reason)$, the household will have a reason (reason? is set on true in the model), else the reason remains on false, and the reason counter (RC) is increased with 1. If the household has reason, it will go through the next steps. The reason counter will also be reset to 1, if the household chooses for a gas boiler in the adoption process.

Is the household aware of the existence of heat pumps?

If a household has a reason, it continues to the awareness check. Some households start with an awareness of heat pumps, however some are not aware, but can become aware during the model run. This happens if the total awareness ($AwarenessLevel_i$) is higher than the awareness threshold.

$$If\ AwarenessLevel_i > AwarenessTHLD \begin{cases} True \rightarrow Household\ is\ aware \\ False \rightarrow Household\ is\ not\ aware \end{cases}$$

1: Through communication with someone in the social network. Each time-step, the household randomly select another household from its social network and checks if that household has a heat pump installed. If so, the household's awareness-level is increased with 1.

2: Through (social)-media. Based on a chance the household becomes aware. If the *media-factor* is higher than a random chance, the household awareness level is increased with 1.

3: Through consulting installers. The installers gain experience directly related to the total installed heat pumps. As the total installed heat pumps in 2017 was only 0,7%, the initial experience by installers is set on 0,05 in 2017. It is also assumed that at an adoption rate of 50%, the experience of installers has reached its maximum with a value of 1. This means that at 0.7% the value is 0.05, and at 50% it should be 1, which translates to the following linear function. When the supplier advice is higher than a random value between 0 and 1, the household's awareness level is increased with 2. It Is assumed that the influence of installers on the awareness level is higher compared to their peers.

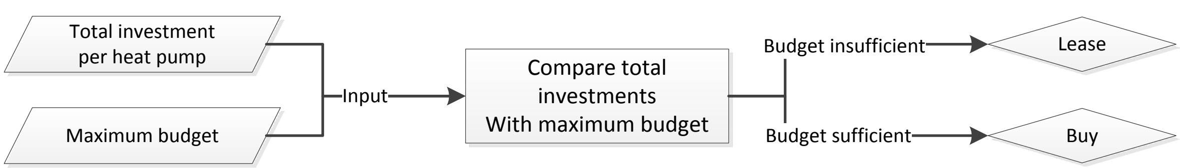
$$supplier\ advice\ = 1.83 \cdot adoption\ rate + 0.087$$

$$supplier\ advice > random\ value\ [0-1] \begin{cases} true \rightarrow aware \\ false \rightarrow not\ aware \end{cases} \quad \text{Eq. (23)}$$

An important note here is that households can only increase their $AwarenessLevel_i$ through consulting installers when they have a reason to, thus when the previous constraint is fulfilled. The other two possibilities can happen regardless whether there is a reason to or not.

The lease or buy decision

The decision by households to either lease or buy is rather simplified. Based on the maximum investment capacity of a household (maximum budget) and the current costs of a heat pump installation (excluding insulation and LTH), the household makes a comparison. If the total investment is higher than the maximum possible investment based on the income, the households will choose for lease. The household will do this for all three heat pump types, thus it can be possible that it will prefer to lease a GSHP while at the same time buy a HHP. If a household prefers to a lease a certain heat pump type, the $LeaseFactor_j$ is set on 0.2. For buying, this factor is set on 1.



6.4 Formalizing the decision module

Here the factors of the decision module are formalized. In

Table 16, one can see the names, abbreviations used in the model and the description, the ranges, whether the factor is static or dynamic and where to find the description.

Table 16: Overview of the factors of the decision module. *Weights not included.

Variable	Abbreviation	Range	Static/ dynamic	Paragraph
The decision factors				
E-label stimulation factor	$ELSF_i$	[0-1]*	Dynamic	6.4.1.1
Social influence	SI_i	[0-1]*	Dynamic	6.4.1.2
Payback time	PT_{ij}	[0-1]*	Dynamic	6.4.1.3
Savings	SAV_{ij}	[0-1]*	Dynamic	6.4.1.4
Hassle Factor	HF_j	[0-1]*	Static	6.4.1.5
Environmental benefit	EB_{ij}	[0-1]*	Dynamic	6.4.1.6
Income factor	IC_i	[0-1]*	Static	6.4.1.7
Investment costs	INV_{ij}	[0-1]*	Dynamic	6.4.1.8
TPB attributes				
Social Norm	SN_i	[0-2]*	Dynamic	6.4.3
Attitude	ATT_{ij}	[0-4]*	Dynamic	6.4.3
Perceived Behavioural control	PBC_{ij}	[0-2]*	Dynamic	6.4.3
Intention	INT_{ij}	[0-8]*	Dynamic	6.4.2

6.4.1 The decision factors

6.4.1.1 E-label stimulation factor

It is assumed that sometime during the model, the government will exert pressure on households to improve their energy-label and thus reduce their carbon footprint. In the model, this is done by looking at the current energy-label. As it is likely that existing houses will fall under regulation such as BENG (see 3.2.4.1). The lower the label a household has, the higher the stimulation by the government will be. Another assumption is that the implementation will be effected gradually, which means it will be increased every year until a certain maximum is reached. The E-label stimulation in the model is equal to the difference between the required energy label and the household's current energy label, divided by the maximum difference of 6. This maximum difference is the difference between the best energy-label in the model, 1, and the worst energy-label, 7. In the model, one has to setup what the required energy label needs to be, and also when it starts. As the implementation is gradually, this means that if for instance the requirement is 1 (best), and the starting year is 2025, that in 2025 the requirement is 6, in 2024 it is 5 and so on. It is not possible that households have negative pressure.

$$ELSF_i = \frac{Elabel_i - ELabelRequired}{6} \qquad \text{Eq. (24)}$$

Where $ELSF_i$ is the E-label stimulation factor, $ELabelRequired$ is the requirement set by the government for a particular year and $Elabel_i$ is the current E-label of the household. Thus in a situation where a household has an E-label of 7, the requirement is 1 and the starting year is 2025, the $ELSF_i$ in 2025 and 2026 is:

$$ELSF_i(2025) = \frac{7-6}{6} = \frac{1}{6} \rightarrow \; ELSF_i(2026) = \frac{7-5}{6} = \frac{2}{6} \rightarrow and\ so\ on$$

6.4.1.2 The social influence

The social influence represents both the neighbourhood effect and the direct communication of households among peers. Although the social network of the households is not in close proximity of another, the effects of the contagion and word-of-mouth are the same. It is assumed that once the $total\ adopters\ in\ SNW_i$ is higher that half the $HHs\ in\ SNW_i$, that the social influence is at its highest. Furthermore, based on model runs and the low influence of the social factor, a factor 2 was added. It is calculated as in Eq. (25):

$$\frac{TotalAdopterSNW_i}{TotalHHsSNW_i} \geq 0.5 \begin{cases} True \rightarrow SF_i = 1 \\ False \rightarrow SF_i = \dfrac{TotalAdopterSNW_i}{TotalHHsSNW_i} \cdot 2 \end{cases} \qquad \text{Eq. (25)}$$

In which $TotalAdoptersSNW_i$ is the total count of adopters in the social network, $TotalHHsSNW_i$ is the total number of households in the social network and SF_i is the social influence.

As can be seen in Eq. (25), the neighbourhood effect is not specified per heat pump type. It is assumed that the effect will be similar for all heat pumps. This means that it is assumed that once a households gathers knowledge about a heat pump through its social network, it will include all heat pumps in its assessment. .

6.4.1.3 Payback time

The payback time is defined by the number of years it takes before a households total investment (CAPEX[9]) is matched by the total savings per year. The payback time in years is given in Eq. (26), by dividing the total CAPEX of the heat pump with the savings per year. It is normalized by using the average lifetime of a heat pump of 25 years. If the payback time in Eq. (26) is higher than 25 years, PT_{ij} is equal to zero. The calculation the payback time factor in Eq. (27) is based on (Palmer

[9] Capital Expenditures

et al., 2015, p110), which means the payback time is equal to the difference between the maximum payback time and the current payback time divided by the maximum payback time and minimum payback time. The maximum payback time is thus set on the lifetime of 25 years, where the minimum is set on 1 year. The CAPEX and savings of a household of Eq. (26) are further explained in 6.4.1.4 and 6.4.1.8.

$$PaybackTime_{ij} = \frac{CAPEXHeatPump_{ij}}{SavingsPerYear_{ij}} \qquad \text{Eq. (26)}$$

$$PT_{ij} = \frac{\max(pt) - PaybackTime_{ij}}{\max(pt) - \min(pt)} = \frac{25 - Paybacktime_{ij}}{24} \qquad \text{Eq. (27)}$$

In which $PaybackTime$ is the payback time of a household for a certain heat pump type in years, $CAPEXHeatPump_{ij}$ is the total capital expenditures of a heat pump (including insulation and LTH), $SavingsPerYear_{ij}$ are the savings of a household per heat pump type per year, PT_{ij} is the normalized payback time factor, $\max(pt)$ is the maximum payback time and $\min(pt)$ is the minimum payback time.

6.4.1.4 Savings

The savings are the difference between the gas bill without a heat pump and the total energy bill with a heat pump. The first calculation is the energy bill of gas when there is no heat pump installed in Eq. (28), which is the base case. The costs here comprise only the gas costs, as it is assumed that all heating currently in households is by heating gas. The total non-heating related electricity usage is assumed to be the same with and without a heat pump. The total yearly energy costs with a heat pump is the use of electricity and the use of gas, dependent on whether it is a HHP or not.

$$BaseYearlyEnergyCosts_i = CGAS \cdot GU_i + CostNetwork \qquad \text{Eq. (28)}$$

$$YearlyEnergyCostsWithHP_{ij} = YearlyGasCosts_{ij} + YearlyElecCosts_{ij} \qquad \text{Eq. (29)}$$

In which $YearlyEnergyCostsWithoutHP$ are the total yearly cost a household spends on the use of gas, $CGAS$ is the costs of gas per m^3, GU_i is the gas usage in m^3 per year, $CostNetwork$ are the network cost, $YearlyGasCosts$ are the total yearly costs by the gas usage of a gas boiler and $YearlyElecCosts$ is the total electricity cost of the electricity usage of a heat pump.

Now that the normal yearly costs of a household are calculated, the energy costs of a situation with a heat pump can be calculated. As the calculation for HHP is different than ASHP and GSHP, two sets of equations are provided.

For ASHP and GSHP, the heat is provided almost completely by the heat pump, and a small part by an electric resistance heater. As is explained in 6.2.1.18, the beta factor says that the heat pump accounts for 97% of the total heat supply, whereas the resistance heat takes up the remaining 3%. As and ASHP or GSHP do not have any gas usage, the yearly energy costs are solely determined by the electricity usage. The electricity usage by the heat pump calculated in Eq. (30) is done by taking the gas usage as a starting point, multiplying this with the conversion factor (from m³ to kWh) and the percentage heat supply it accounts for ($GU_i \cdot \gamma \cdot 0.97$) and dividing it with the COP (COP_j). The electricity usage of the electric resistance heater is calculated in a similar way, however, since the COP of such an heat is 1, it is not divided by the COP. The sum of the electricity usage is then multiplied by the electricity cost per kWh.

ASHP & GSHP

$$YearlyEnergyCostsHP_{ij} = (kWhUseHP + kWhUseEHeater) \cdot CElec$$

$$YearlyEnergyCostsWithHP_{ij} = \left(\frac{GU_i \cdot \gamma \cdot 0.97}{COP_j} + 0.03 \cdot GU_i \cdot \gamma\right) \cdot CElec \qquad \text{Eq. (30)}$$

Where GU_i is the gas usage, γ is the conversion factor from gas to electricity, COP_j is the Coefficient of Performance of the heat pump and $CElec$ is the electricity cost per kWh.

For HHPs, the heat pump is assisted with a gas boiler. The amount of heat the gas boiler supplies is 25%, as is shown in 6.2.1.18. The calculation of the electricity usage of the heat pump in Eq. (31) is similar to that of ASHP and GSHP. In Eq. (32) the yearly gas usage by the gas boiler is simply calculated by taking the current gas usage and multiplying it with 25% ($BackUpGas$). The total yearly energy costs with a hybrid heat pump is then the yearly electricity usage multiplied with the electricity cost per kWh plus the yearly gas usage by the gas boiler multiplied with the gas costs per m³ plus the network costs, as can be seen in Eq. (33). The latter is different from the ASHP and GSHP calculation, which is because of the assumption that a households completely disconnects from gas when switching to a ASHP or GSHP.

HHP

$$YearlykWhUseHP_{ij} = \frac{GU_i \cdot (1 - BackUpGas) \cdot \gamma}{COP_j} \qquad \text{Eq. (31)}$$

$$YearlyGasUseGasBoiler = GU_i \cdot BackUpGas \qquad \text{Eq. (32)}$$

$$YearlyEnergyCostsWithHP_{ij} = YearlykWhUseHP \cdot CElec + YearlyGasUseBoiler \cdot CGAS + CostNetwork \quad \text{Eq. (33)}$$

In which the GU_i is the gas usage per year, $BackUpGas$ is the percentage of the total heat supply the gas boiler provides, γ is the m^3 gas to kWh conversion factor, COP_j is the COP of the heat pump, $CElec$ is the electricity cost, $CGAS$ is the gas cost and $CostNetwork$ are the network costs by the DSO and gas and electricity suppliers.

For heat pump types, the yearly expenditures are now known, which means the savings per year can be calculated, shown in Eq. (34). This is done by subtracting the total yearly energy cost with a heat pump from the costs in the situation without one. The normalized savings (Eq. (35)) are the savings per year divided by the yearly energy costs without a heat pump.

$$SavingsPerYear_{ij} = BaseYearlyEnergyCosts_i - YearlyEnergyCostsWithHP_{ij} \quad \text{Eq. (34)}$$

$$SAV_{ij} = \frac{SavingsPerYear_{ij}}{BaseYearlyEnergyCosts_i} \quad \text{Eq. (35)}$$

6.4.1.5 The hassle factor

The hassle factor represents all the inconvenience a household can expect from installing a heat pump, thereby being a limiting factor on heat pump adoption. The hassle factor is a static variable, and is based on the number provided by (Snape et al., 2015), meaning that the hassle factor HF_{ij} is equal to 0.9 and 0.6 for GSHP and ASHP. As HHPs weren't part of their study, a value has to be assumed. Since a HHP does not require, drilling, LTH, or insulation the value is considerably lower, at 0.3.

$$HF_j(HHP) = 0.3,\ HF_j(ASHP) = 0.6,\ HF_j(GSHP) = 0.9$$

6.4.1.6 Environmental benefit

The environmental benefit is based on the comparison between the total CO_2 emissions in the base situation without a heat pump and the situation with a heat pump installed. The yearly CO2 emissions in the base case (Eq. (36)) is found by simply multiplying the household's gas usage with the emission factor of gas (α). The total yearly CO_2 emissions for a heat pump are found by summing the CO_2 emissions of the electricity usage and the gas usage (Eq. (37)).

$$YearlyBaseCO2_i = GU_i \cdot \alpha \quad \text{Eq. (36)}$$

$$YearlyCO2withHP_{ij} = CO2GasUse_{ij} + CO2ElecUse_{ij} \quad \text{Eq. (37)}$$

In which GU_i is the yearly gas usage, α is the CO2 emissions per m³ gas, $YearlyBaseCO2$ are the total CO2 emissions without a heat pumps, $CO2GasUse_{ij}$ is the total CO_2 emitted by the use of gas and $CO2ElecUse_{ij}$ is the total yearly CO_2 emitted by the use of electricity.

Just like the savings, the calculation of the environmental benefit is different for HHPs compared to ASHPs and GSHPs. For the latter two, the CO2 emissions for the electric resistance heater is found by multiplying the gas usage per year, with the conversion factor γ, the share of total heat supply the heater provides and the emission factor for electricity in the Netherlands (β) (Eq. (38)). In the following equation (Eq. (39)) the CO2 emissions for the heat pump are calculated. The equation for the amount of kWh is similar to that of the savings in 6.4.1.4, and is also multiplied with the emission factor for electricity. The heat is fully provided by electricity, thus the CO2 from gas usage is 0 in Eq. (41). The emissions from electricity usage is the sum of the emissions from the heat pump and the resistance heater, see Eq. (40).

$$YearlyCO2EBackUp = \beta \cdot GU_i \cdot \gamma \cdot 0.03 \qquad \text{Eq. (38)}$$

ASHP & GSHP

$$YearlyCO2HP_{ij} = \beta \cdot \left(\frac{GU_i \cdot (1 - 0.03) \cdot \gamma}{COP_j} \right) \qquad \text{Eq. (39)}$$

$$CO2ElecUse_{ij} = YearlyCO2EBackUp_{ij} + YearlyCO2HP_{ij} \qquad \text{Eq. (40)}$$

$$CO2GasUse_{ij} = 0 \qquad \text{Eq. (41)}$$

In which β are the CO_2 emission per kWh electricity usage, $GU_i$is the gas usage per year, γ is the conversion factor from m³ gas to kWh electricity, $YearlyCO2EBackUp$ is the total CO_2 emitted by the electric resistance heater and $YearlyCO2HP_{ij}$ is the yearly CO2 emitted by the heat pump.

For HHPs, instead of the resistance heater, the CO_2 emissions next to the heat pump originate from the gas boiler, see Eq. (42). The next equation (Eq. (43)) is similar to that of ASHP and GSHP, except for the gas boiler. The total emitted CO2 per year of the electricity usage is solely determined by the heat pump (Eq. (44)), and the emittance from gas usage is based on the gas usage by the gas boiler (Eq. (45)).

$$YearlyCO2GasBoiler = \beta \cdot GU_i \cdot BackUpGas \qquad \text{Eq. (42)}$$

HHPs

$$YearlyCO2HP_{ij} = \beta \cdot \left(\frac{GU_i \cdot (1 - BackUpGas) \cdot \gamma}{COP_j} \right) \qquad \text{Eq. (43)}$$

$$CO2ElecUse_{ij} = YearlyCO2HP_{ij} \qquad \text{Eq. (44)}$$

$$CO2GasUse_i = YearlyCO2GasBoiler \qquad \text{Eq. (45)}$$

In which $BackUpGas$ is the percentage of the total heat supply the gas boiler provides and $YearlyCO2GasBoiler$ is the total CO2 emitted by the use of gas with the gas boiler.

For all heat pump types, the normalized environmental benefit is calculated as shown in Eq. (46).

$$EB_{ij} = \frac{YearlyBaseCO2_i - YearlyCO2WithHP_{ij}}{MaxCO2} \qquad \text{Eq. (46)}$$

Where $MaxCO2$ is a value that is based on results of the model. The highest $YearlyBaseCO2$ of the households in the dataset was around 6300, which was rounded to 6000.

6.4.1.7 Income factor

The income is a widely used factor in innovation literature as it is described in 3.2.2. The implementation in the model is rather simplistic. It is represented by ICF_i and is acquired by dividing the income by the highest income value possible of 6 (see 6.2.1.3).

$$ICF_i = \frac{IC_i}{6} \qquad \text{Eq. (47)}$$

6.4.1.8 Investment costs

In this study, the assumption is that there is no LTH or insulation required when considering a HHP. The reason is that the gas boiler and heat pump can work together efficiently, making insulation and LTH not an absolute necessity, although it is generally still advised to do so. The consequence is that the way of calculating the total investment and savings is different for HHPs opposed to ASHP and GSHP. Furthermore, there are two types of total investment costs calculated. As a result of the lease or buy decision. One of the advantages when leasing, is that the upfront investment is considerably lower compared to buying a heat pump. In Eq. (48), for ASHP and GSHP, and Eq. (50), for HHP, the first type of total investment is shown. The total heat pump costs are multiplied with the lease-factor, which is 0.2 if a household wants to lease, and 1 when it prefers to buy (see 6.2.1.17). For ASHP and GSHP, the costs for LTH and insulation are added. The sum is the multiplied with the percentage that a household has to pay based on the percent subsidized (see 6.2.2.2). In Eq. (49) and Eq. (51) the total CAPEX of the heat pump is calculated, irrespective of the lease or buy decision. The outcome of these calculations is needed to determine the payback time in 6.4.1.3. When leasing, the household still has to pay the entire

CAPEX, it is only spread over a number of years. Therefore the payback time cannot use the upfront CAPEX. The difference between the upfront CAPEX ($CAPEXHPUpfront_{ij}$) and the total CAPEX ($CAPEXHeatPump_{ij}$) is only the lease factor. The consequence is that when a household only wants to buy, both CAPEX factors are the same, as the lease factor is then 1.

For ASHP and GSHP

$$CAPEXHPUpfront_{ij} = (CostHeatPump_{ij} \cdot LeaseFactor_i + CostLTH_i + CostInsulati \\ - PercentSubsidized) \quad \text{Eq. (48)}$$

$$CAPEXHeatPump_{ij} = \left(CostHeatPump_{ij} + CostLTH_i + CostInsulation_i\right) \cdot (1 - Perce \quad \text{Eq. (49)}$$

For HHPs

$$CAPEXHPUpfront_{ij} = \left(CostHeatPump_{ij} * LeaseFactor_i\right) \cdot (1 - PercentSubsidized) \quad \text{Eq. (50)}$$

$$CAPEXHeatPump_{ij} = CostHeatPump_{ij} \cdot (1 - PercentSubsidized) \quad \text{Eq. (51)}$$

In which $CAPEXHPUpfront_{ij}$ is the total capital expenditures that a household has to pay upfront, $CostHeatPump_{ij}$ is the total heat pump cost, $LeaseFactor_i$ is the lease factor which follows from the lease or buy decision (either 0.2 or 1), $CostLTH_i$ is the cost for low temperature heating, $CostInsulation_i$ is the cost for insulation and $PercentSubsidized$ is the amount of the total payment that is subsidized by the government (can be altered in the model).

Finally, in Eq. (52) the investment factor is calculated. This normalized by using the maximum budget that a household has based on its income (see 6.2.1.9)

$$INV_{ij} = \frac{MaxBudget - CAPEXHPUpfront_{ij}}{MaxBudget} \quad \text{Eq. (52)}$$

6.4.2 Merging the factors with the Theory of planned behaviour

As is explained in 2.2.2 the theory of planned behaviour is the theoretical model for the decision making of the agents in this study. Jensen (2017) provided a way to implement the TPB into a mathematical procedure, which makes it possible to insert it into an ABM. Following from the TPB, all households will also have an Attitude ATT_{ij}, a perceived behavioural control PBC_{ij}, and a Social Norm SN_{ij}. The intention of a household per heat pump type is as follow.

$$ATT_{ij} + SN_{ij} + PBC_{ij} = INT_{ij} \qquad \text{Eq. (53)}$$

Where i represent a household, and j the heat pump type. INT_{ij} is the intention of a household for one of the heat pumps, ATT_{ij} is the total Attitude, SN_{ij} is the total Social Norm, PBC_{ij} is the total Perceived Behavioural Control. Households thus have a different attitude, PBC, and social norm for each heat pump.

6.4.3 Determining the attitude, perceived behavioural control and the social norm

In 5.3.3 it is explained which decision factors belong to which TPB attribute. This results in Eq. (54) Eq. (55) and Eq. (56). All factors are additive. The hassle factor has a inhibitory effect, as it is subtracted.

$$ATT_{ij} = EB_{ij} + PT_{ij} + SAV_{ij} - HF_j \qquad \text{Eq. (54)}$$

$$PBC_{ij} = ICF_i + INV_{ij} \qquad \text{Eq. (55)}$$

$$SN_{ij} = SF_i + ELSF_i \qquad \text{Eq. (56)}$$

Again, i represents a household, and j the heat pump type. Where ATT_{ij} is the Attitude, PBC_{ij} the Perceived Behavioural Control, SN_{ij} the Social Norm, EB_{ij} is the environmental benefit, PT_{ij} is the payback time, SAV_{ij} is the savings, HF_j the hassle factor, ICF_i the income factor, INV_{ij} the investment costs, SF_i the social influence and $ELSF_i$ the E-label stimulation factor. One might notice that the three TPB attributes are all added to get the intention, and that the attributes separately are also a sum of certain factor. The same intention can be calculated by simply adding all decision factors. The reason that the TPB attributes are incorporated into the model is for the sake of the structure and overview. The TPB provides the basic structure that is used throughout the thesis, therefore it is useful to keep it that way, also in the model. Would the model become very sluggish due to these extra calculation, one might argue to model the calculation of the intention as simple as possible. However, the model is quite fast, therefore these extra calculation pose no further problems.

6.4.4 The actual control of the households: the resources available check

Before a household moves to the adoption process, first the resource check is performed. This is done by checking whether the house type is suitable (see 6.2.1.6) and when the maximum budget (see 6.2.1.9) is higher than the upfront investment. If one of this conditions fails, the intention for the corresponding heat pump is set on 0.

6.4.5 The adoption process

As is explained in 6.4.2, the households all have an intention for the three heat pump types. Logically, they also have an option not adopt, which essentially means that they prefer a gas boiler. This leaves a household with 4 options: a HHP, ASHP, GSHP or a gas boiler. As households can be autonomous in an agent based, model, they should be able to make a choice between these four options in the model. The choices are made by calculating a certain probability per HP type and gas boiler. The higher the intention, the higher this probability will be. Before such probabilities can be calculated, first the intention for the gas-boiler should be calculated, else it is impossible to choose one. The gas boiler intention is calculated as follows:

$$GasBoilerInt_i = MaxInt - \sum_{j=1}^{3} INT_{ij} \qquad \text{Eq. (57)}$$

Where $GasBoilerInt_i$ is the intention value of the gas boiler, $MaxInt$ is the maximum intention value and INT_{ij} is the intention for a household per heat pump. The sum of the intention for the three heat pump types is thus subtracted from the $MaxInt$. For the calculation of the gas boiler intention, a maximum intention ($MaxInt$) is thus needed. This is a value that represents the sum of all the intention of the three heat pump types and the gas boiler. The value of this parameter affects the speed of the adoption process strongly. As can be seen in Eq. (57), the higher the $MaxInt$ is, the higher the intention of the gas boiler will be, and thus also the chance that a household will choose for a gas boiler. The max intention is determined through calibration. A total adoption of 50% of the total households is chosen as the calibration value. As it cannot be known what the total adoption in 2050 will be, there are no values available on which the model can be calibrated. With a total adoption of 50% in 2050, the differences and uncertainties with the experiments in the next chapter can be best seen. Calibrating the model at 100% would not make sense this way, as the influence of certain measures cannot be evaluated. The calibration led to a $MaxInt$ of 23.5. A further explanation can be found in B.7.

Now that the gas boiler intention and max intention are known, the probabilities per alternative can be calculated, see Eq. (58) and Eq. (59).

$$P(HP_{ij}) = \frac{INT_{ij}}{MaxInt} \qquad \text{Eq. (58)}$$

$$P(GB_i) = \frac{GasBoilerInt_i}{MaxInt} \qquad \text{Eq. (59)}$$

Where $P(HP_{ij})$ is the probability that a household adopts the heat pump, INT_{ij} is the intention per heat pump type per household, $P(GB_i)$ is the probability that a household adopts a gas boiler and $GasBoilerInt_i$ is the intention for a gas boiler of a household. The choice of which option to choose depends on a random value between 0 and 1, that is different each time step, and on the probabilities per option. The probabilities provide the range between 0 and 1 per option. The higher the probability, the higher the range. If the random value falls within this range, the household chooses the corresponding option. This is best explained by using a hypothetical situation presented in Table 17 and a simple decision tree in Figure 18.

Table 17: Hypothetical situation of the intention and probabilities of a single household

$MaxInt$ = 22			Adoption Range	
Option	**Intention**	**Probability (sum=1)**	**Lower bound**	**Upper bound**
Gas boiler	9.5	0.43	0	0.43
HHP	5.5	0.25	0.43	0.68
ASHP	4	0.18	0.68	0.86
GSHP	3	0.14	0.86	1

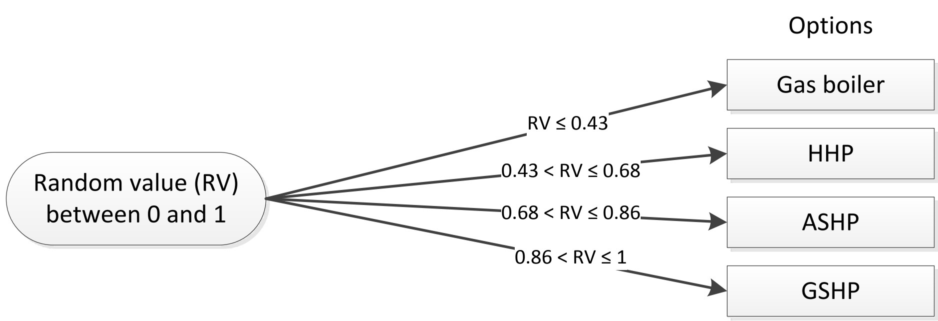


Figure 18: Decision tree on how a household chooses an option

Thus if the random value is lower than 0.43, the household chooses a gas boiler, if it is higher than 0.43 and lower than 0.68, it prefers a HHP, and so on. In this situation, the total chance on a heat pump compared to a gas boiler is thus 57% versus 43%.

6.5 Assigning weights to the different household groups

The households are divided into household groups, as is described in 3.2.6. This means that these types behave differently, and thus will factors weigh different per type. It is also in line with the description of the TPB by Ajzen (1991). The weights can be seen as a representation of the strengths of each of the beliefs. As there an empirical study into the beliefs of households of the decision factors (see 6.3), other sources are needed. The report by Motivaction (Randsdorp & Schoemaker, 2014) is used to assign the weights, as this reports uses the household groups based which are derived by the mentality types. The report does not match perfectly with all decision factors, however, it is possible to take the most important factors per household group. In the model, this is done by setting the weights of all factors on 1, with the exception of one or two factors that are very important to a group. If one factor is more important than the others, it is given a weight of 2. If two factors are important, both have a weight of 1.5. The weights can be seen in Table 18.

Table 18: Weights per factor for the four household groups

	Unaware energy-users	**Pragmatic comfort seekers**	**Environmentally aware improvers**	**Faithful environmentalists**
Payback time	2	1.5	1	1
Savings	1	1	1	1
Investment costs	1	1	1	1
Hassle	1	1.5	1	1
Social influence	1	1	1	1.5
Pressure	1	1	1	1
Environmental Benefit	1	1	2	1.5
Income	1	1	1	1

Below descriptions are all based on (Randsdorp & Schoemaker, 2014):

The **unaware energy-users** for instance do not care about the environment and doubt humanity can do something about climate change. They do care about their own problems, which is why it is only important what the personal benefit is. That is why the payback time is essential for this group and is given a weight of 2.

The **pragmatic comfort seekers** also only invest in something if they can see the personal utility of the investment. Logically, the payback time is therefore also an important factor. They also place comfort above a lower energy bill and does not really care whether natural gas is replaced by renewable energy sources. Promoting renewables must be to the point and practical. This is why the hassle factor is important for this group. Insulation, low temperature heating instead of the current radiators and possible digging are aspects that are not boding well for the comfort levels, and are seen as impractical. The hassle factor and payback time both have a weight of 1.5.

As the name implies, the **environmentally aware improvers** care about the environment. They are willing to pay a bit more for energy produced by wind, solar and other renewable sources. Therefore the weight for the environmental benefit is set on 2 for this group.

The last group are the **faithful environmentalists**, a group also concerned with the environment. At the same time, this group is very much concerned with the neighbourhood, and care greatly about society. Therefore, this group is also sensitive to influence from members of their social network. Both the environmental benefit as the social influence has a weight of 1.5.

6.6 Stochasticity in the model

Stochasticity is an important aspect within agent-based modelling, as this makes sure that the systematic uncertainties are captured in the model. Stochasticity is present at the initialization and during a model run. Within Netlogo, pseudo-random number is generated based on the date and time. This makes sure that each run the sequence of the agents is different. Within in the model, randomness can be found in multiple variables.

- **Social Network:** Stochasticity can be found in the social network, as households randomly connect with other households. Also, the households talk randomly to one member of their social network so they can become aware.
- **Reason:** The households are randomly assigned an initial reason between 1 and 10, and there is also stochasticity in the failure chance.
- **Energy-label:** Every tick, a random selection of households improves their energy-label
- **Awareness:** The initial awareness level of the households is random, as well as the threshold level.
- **Adoption process:** The household base their decision on a random value each tick when they come to choose for a heat pump.

6.7 Assumptions made during modelling:

Throughout the thesis so far, assumptions for the model are mentioned and explained. However, this doesn't cover all assumptions that were made during the conceptualization, formalization and implementation. Therefore, these assumptions are described here.

When a household switches from a gas-boiler to a heat pump, this will mean that there is no more gas usage by that particular household. Therefore it is assumed that the energy of the total gas usage of a household previous to the HP instalment will now be provided by the heat pump. Since a heat pump uses electricity, a conversion factor is used from to convert m^3 to kWh, which is around 10. This is the result of using the caloric value of natural gas of 35,17, and dividing it with the energy of one kWh of 3.6MJ. The assumption is also made that this conversion is an accurate representation of the electricity usaged by a heat pump. Energy losses in the heat distribution system and in the gas boiler are thus not taken into account.

When a household has installed a heat pump, it is assumed that the heat pump will last until the end of the simulation time, thus 2050. Although this is unrealistic as heat pumps have an average lifetime of 25 years, and the simulation time is 33 years, the goal of the study is to analyse the overall adoption of HPs. In that sense, it doesn't matter if a household replaces a HP after it breaks down, but only whether a household has a HP or not. Furthermore, when a heat pump is over its lifetime, it is likely that not all parts have to be replaced. With GSHP for instance, there are likely no drilling works needed than with the first heat pump. So it is assumed that households do not go back to gas boilers and that this has no further influence on the total adoption. It could have influence on the adoption per heat pump type.

As the simulation step is 1 year, seasonal differences are not taken into account. This means that the weather and climate do not play a role.

The reliability per different types of heat pumps is not taken into account. It is assumed that the reliability of the heat pumps is similar among the different types.

When a household chooses for an ASHP or GSHP, it is assumed it will disconnect itself from the gas grid completely. This means that households also have to find an alternative for cooking, which will be electricity. Besides the electricity needed for the heat pump there is thus also electricity needed for cooking. However, as an average household needs around 175 to 225 kWh a year for electric cooking, the share in the total electricity usage of 7000 kWh (including a GSHP with a COP of 4), is 225/7000 = 3%. As these effects are very small is it chosen to leave this out of scope.

Education is a relevant factor. Income and education are generally related, according to CBS (2011), thus when the income is at a high scale, the education is generally higher as well. Therefore, education is left out of the model.

When a household makes an assessment about the savings payback time and investment cost, the current energy prices are used. In reality, during the lifetime of a heat pump, these energy costs change. A net present value calculation would be more realistic. For simplicity reasons however, this was not included. So at the time of the decision, households no large price changes.

The same argument is true for the environmental benefit. One could expect that the average CO_2 per kWh will decrease over the years, thus leading to a higher environmental benefit. Furthermore, the fact that household could have a *green* energy contract with their supplier could improve the environmental benefit even more in the perception of the households.

The leasing function is modelled rather simplistic, as the household only checks if its budget is sufficient. This could also lead to the situation where a single household prefers to buy one heat pump type, while it wants to lease another. Whether this is realistic, is questionable. Furthermore, there are multiple leasing constructions possible, with different durations, risks, interest rates and upfront costs. Loaning a heat pump is another construction, next to leasing or buying, this was left out of the scope

6.8 Verification

The goal in verification is to check whether the model is working as is intended in the conceptualization of the model. According to van Dam et al. (2013), there are four main verification parts:

1. Recording and tracking agent behaviour, in which relevant metrics are identified and recorded.
2. Single-agent testing, in which the behaviour of a single agent is verified.
3. Interaction testing limited to minimal model, in which the interaction between agents is tested.
4. Multi-agent testing, in which the emergent behaviour of multiple agents is examined.

During implementation of the model in Netlogo, all procedures where verified in a iterative manner. This included verification of all four parts above. All single verification steps are not properly documented. However, would all checks be written out, they would look similar to this:

> 1: The pressure should increase from the moment it starts and is dependent on the height requirement. If the requirement is 7, the pressure of all households should be zero. At the same time, when all households have an energy-label of 1, the pressure should also be zero. **Both Confirmed**

2: The payback time should be high when the subsidy-factor is 100%, as the investment is free. **Error.** A 100% subsidy-factor led to zero lifetime investments. Dividing that by the savings led to a payback time of 0. **Recoded** with an if condition**. Reevaluated. Confirmed.**

The reason was one of the procedures where verification led to insight in the incorrect modelling. The reason-counter was first randomized between 0 and 10, and if a household would only have a reason when this counter reached 10. However due to the randomizer, a very unequal distribution of households what would have a reason was formed, which in turn led to a very high adoption in one year and a very low in another year. A intermediate fix ensured an uniform distribution. However the real fix was when it came to the understanding that the autonomy of the agents was very limited in the model. This autonomy was implemented in the model by relating the reason-counter to a certain chance that a household could have a reason. Which means that each time step, a household could have a reason, and thus possibly adopt a heat pump. This way, the distribution of agents that have a reason each time step also became more even.

Another issue was found in the formalization of the environmental benefit step, as all households had exactly the same environmental benefit per heat pump type. This was due the calculation, that is based on only households variable, the yearly-gas-use. The calculations were in such a way, that in the end, it didn't matter how much emissions were saved. This was corrected with a fixed maximum CO_2 level, which was used for normalization

The energy-label requirement for households was only 1/6 or 0 after it was fully implemented. Every household thus has a very low stimulation, whereas some still had an energy label of 7 and thus should have a higher value. The problem was caused by a wrong minus factor.

6.9 Conclusion

The goal of this chapter was to accurately describe how each variable of the model was implemented. First a distinction was made between the household's variables and the parameters of the environment. Five variables from the EDM dataset provide the basis for the model, as many other variables are based on these. Many variables have a rather simplified implementation, such as the costs variables for the LTH, insulation and heat pump itself. When a households has to go through the conditional checks in the model, it first checks if it has a reason to, based on a counter. If the counter has reached 10, it will go to the next check, the awareness. A threshold awareness value is used that must be passed by a household.

The theory of planned behaviour is formalized by summing all attributes, leading to an intention. The intention is converted into an adoption probability, including an intention of a gas boiler. The higher the adoption probability, the higher the chance a household adopts the corresponding option. Though the eight decision factors and their corresponding weights, the intention can change. Excluding the weights, all decision factors have a normalized value between 0 and 1. In Chapter 5, was described which decision factor belongs to what TPB attribute. In this chapter, the decision factors where summed according to the description in the previous chapter. Weights were assigned to some factors, based on the description of the household groups. As there was no clear indication per decision factor, it was decided to put extra weight on only one or two factors. Stochasticity is present in multiple variables, such as the social network, awareness, reason and energy-label.

This chapter forms the basis of the model, and thus is essential in answering the research question "*What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using Agent Based Modelling?"*. Through the model, the financial incentives can be tested, which is further explained in Chapter 7.

Part III

Now that the model is complete, the financial incentives can be evaluated. The lease-or-buy decision, elabel requirement, gas price growth rate and percent subsidized will all be experimented with. The experiments will be with fixed financial incentives, but also with temporary and adaptive settings. This will presented in Chapter 7. In Chapter 8 the validation, sensitivity analysis and model use is handled.

Chapter 7: Exploration of the financial incentives

Chapter 8: Validation, Sensitivity analysis and Model use

7

Exploration of the financial incentives

In this chapter, the model is put to use by performing experiments. Through experimentation, one can explore the effect of multiple combinations of policy settings and external variables on key measures of interest. The experimental design is essential in answering the research question, which is: What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands? Firstly, the basic experimental design is handled in 7.1. Here the hypothesis and basic settings will be discussed. Subsequently, in 7.2, the general behaviour of the model is analysed and compared with a so called macroscopic regularity of interest. In paragraph 7.3 the individual influence of the incentives is presented and analysed, where in 7.4 the combined influence of the gas price growth and subsidy is used in a scenario analysis. In 7.5 the experiments are taken to the next step by analysing what temporary measures such as a high gas price or subsidy, influence the adoption rates, as well as an experiment with a high awareness and reason for households to adopt when a heat pump system is fully subsidized. All results presented should be viewed as within the scope of the research and the made assumptions.

7.1 Tested hypothesis and initial settings for the simulation

Experiments for ABM are generally in form of two types of hypothesis (K. H. van Dam et al., 2013): (1) under the specified conditions, a macroscopic regularity of interest emerges from the designed agent-based model, and (2) a range of clearly identifiable emergent behaviours and regularities that can be established from this agent based model of a system. The first hypothesis is aimed at testing by comparing real-world observed patterns with the patterns of the model. If the emergent patterns are similar, the hypothesis is confirmed. The second hypothesis is aimed at exploration and is more difficult to falsify. This depends on the goal of the study. Both hypotheses are tested in this study, which means two experimental setups are created. The first hypothesis is further explained and handled in 7.2, whereas the second hypothesis is handled the subsequent paragraphs 7.3, 7.4 and 7.5.

For all experiments, the settings of the external variables is according to Table 20. Meaning that the BENG measure kicks off in the same year for all experiments (if active). In Table 19, the main settings for the base run are presented. The base run is used to analyse the influence of the incentives used in the experiments. Following from Table 19, the gas price increase is set on the average inflation level of 2% in the Netherlands. With a starting value of 0.61 and a 2% increase over 40 years, this means that in 2050, the gas price will be around 1.34 €/m³, which is slightly higher than the price assumed for biogas production in 2050 by (Rooijers et al., 2015). BENG regulation is currently only for newly build houses (see chapter 3), thus for the existing households this is set on 7, which means that it is essentially turned off. Leasing is turned off as well in the base run. The number of replications is set to 100.

Table 19: parameters setting for the first experiment. N.a = not available

Variable	**Unit**	**Value**
Gas price initial value	€/m³	0.61
Electricity price starting value	€/kWh	0.161
Electricity price increase	%	2
BENG starting year	Year	2025
Emission factor electricity	kg CO_2/kWh	0.355

Table 20: Settings external variables for all experiments.

Variable	**Unit**	**Value**
Gas price increase	%	2
BENG-regulation	n.a.	7
Subsidy	%	25
Lease-on?	n.a.	False

It must be noted that during the experimentation of all experiments in this chapter, the percentage subsidised is different from the value used in the calibration in 6.4.5, 20% vs 25%. Therefore the base runs, used in almost all plots for comparison, will not result in 50% adoption in 2050, but instead a slightly higher value, due to the higher subsidy value.

7.2 The general behaviour of the model for 100 years

The first type of hypothesis described in 7.1 is aimed at analysing whether the behaviour of the model is similar to observed patterns in literature. More specifically, it was tested if it would fit with Rogers's diffusion of innovation. Rogers theory holds that innovation diffusion generally follows an S-curve. The first hypothesis is therefore:

The emergent pattern of the total heat pumps installed is in the shape of an S-curve

This hypothesis automatically implies a bell-shaped curve is true for the adopters per year. The setting of the four parameters are fixed as shown in Table 19. For the purpose of this experiment, the time frame was extended towards 2117, because in 2050 the behaviour does not seem to be stable yet, see Figure 20.

The adoption is at its peak around the year 2045, then the adopters per year declines. The behaviour of the model has a clear S-shaped curve in Figure 20 with a corresponding bell curve of the total adopters per year in Figure 21. Compared to Rogers's curve (Figure 19), the S-curve is steeper in the beginning, and the bell-curve is not a perfect normal distribution as is the case with Rogers curve. In the model, the innovators, early adopters and early majority are thus quicker to adopt, and the late majority and laggards are slower.

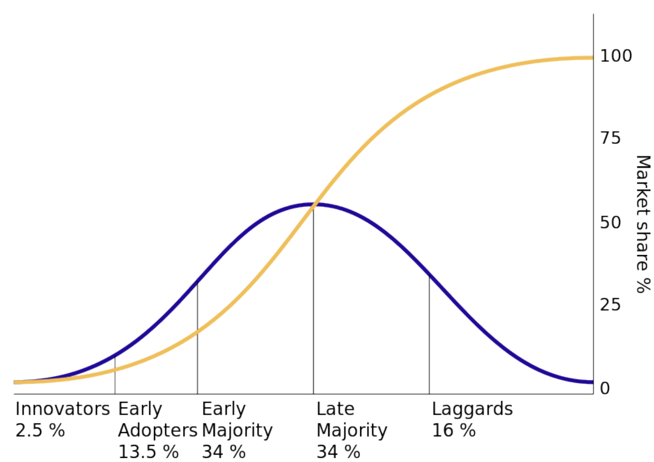


Figure 19: Rogers S-curve of innovation and the adopter categories (Rogers, 1962)

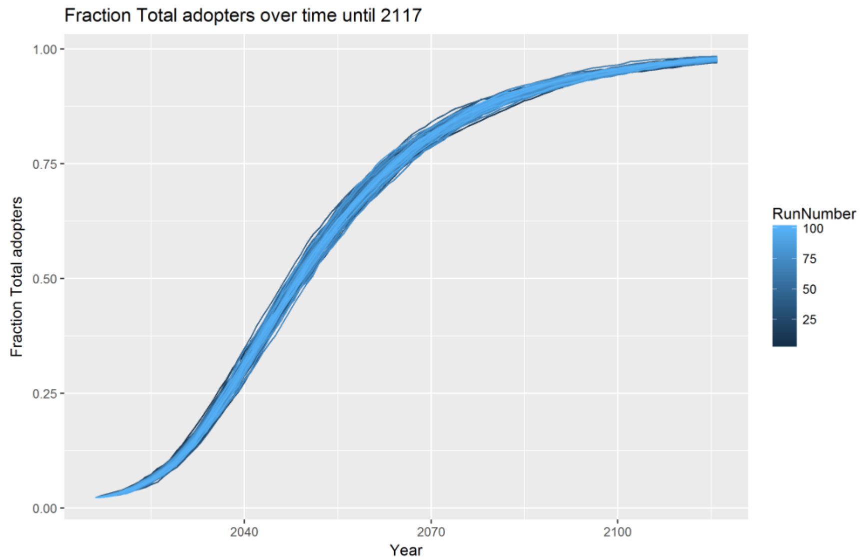


Figure 20: The behaviour of the model when the timeframe is from 2017 to 2117.

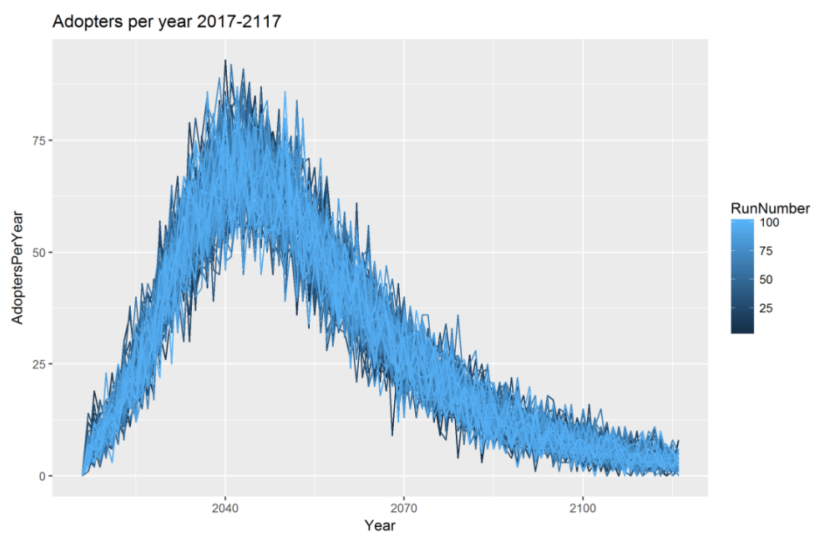


Figure 21: The bell-curve of adopters per year from 2017-2117

In Figure 21, some strong oscillations can be observed for the adopters per year. This is due to the fact that the number of households that have a reason to adopt is different each year, and of those households that have a reason to adopt, there are differences in the number that adopts a heat pump.

7.3 Exploration of the financial incentives compared to the base run

Now that it has been established that the models behaviour is similar to an S-curve, the influence of the financial incentives can be assessed, as well as the results of the run with the base settings.

7.3.1 Experimental design

The overview of the experimental setup can be found in Figure 22. The input parameters represent the financial incentives. Then based on the settings of these parameters and the external variables, a number of different outputs are extracted from the simulation.

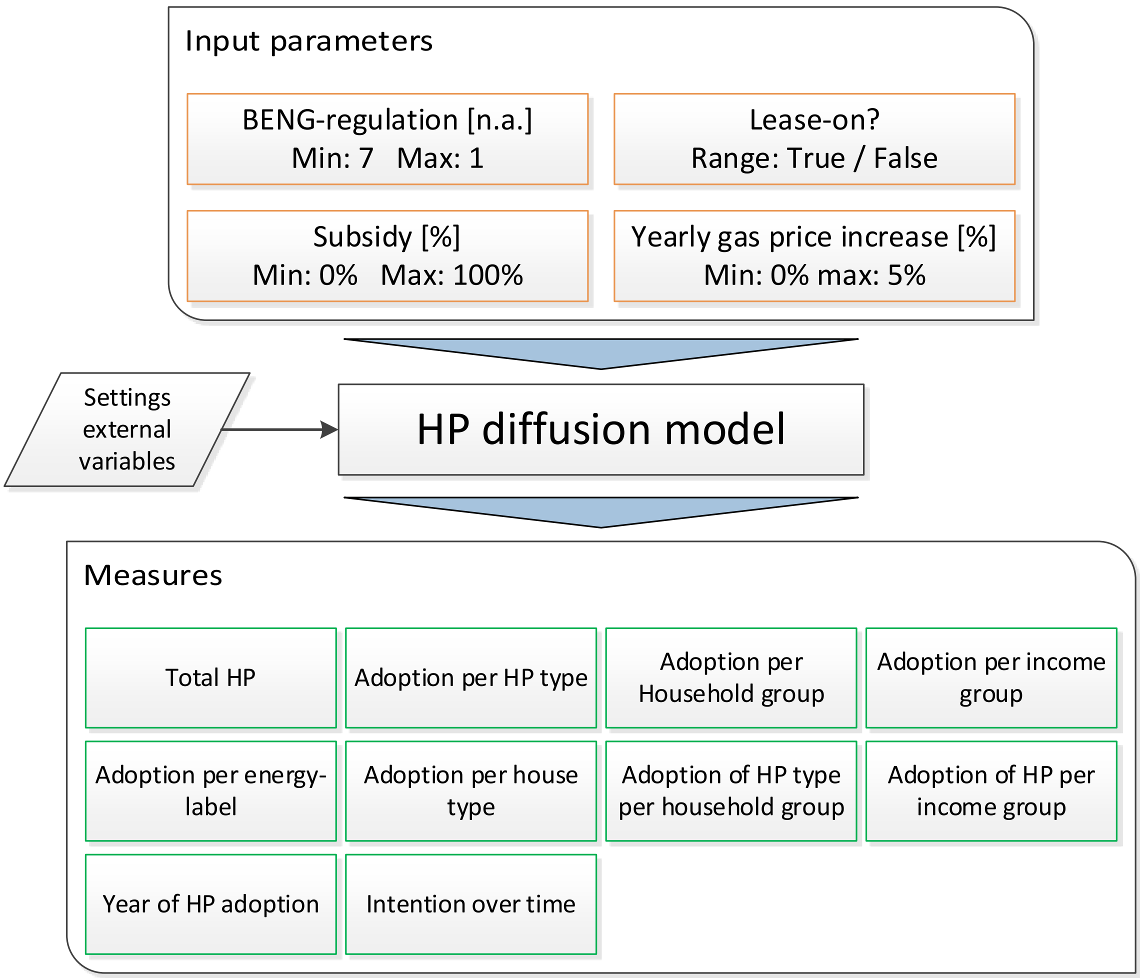


Figure 22: Schematic overview of experimental setup

The outputs are in the form of statistics about the adoption, such as percentage of installed heat pumps, but also per heat pump type, per household group and per income group. The parameters are governmental measures and market developments, more specifically, these are (1) the gas price increase, (2) subsidy, (3) BENG[10]-regulation (insulation) and (4) the lease or buy decision.

[10] Bijna EnergieNeutraal Gebouw

As can be seen in Figure 22, the maximum yearly gas price increase is 5%, resulting in a price of 4.30 €/m³ in 2050, when starting with 0.61 €/m³ in 2017. This boundary is already high, as it is lot higher than highest price evaluated by CE Delft in their study about the future of residential heating systems (CE Delft, 2015). The BENG-regulation is ranges from 1 (A+ energy label) to 7 (G energy-label). The minimum is 7, as that represents the worst energy label. A minimum requirement is thus equal to the worst energy-label. The subsidy ranges from completely subsidized (100%) to zero subsidy.

In Figure 1, one can also notice the *setting external variables* block on the left. These are some important external variables next to the parameters. These will be set on a fixed value for all experiments as is described in Table 20, paragraph 7.2. Each model run will go for 33 years, from 2017 to 2050. To guarantee reproduce ability of the results, a fixed random seed is used each experiment. As each experiment has 100 replications, the random-seed is set from 1 to 100.

The individual influences of each parameter is analysed in this paragraph. Thus all parameters will range according to the values given in Table 21.

Table 21: The parameters and their corresponding values. The steps column indicates how many different values are possible within a parameter

Name	Unit	Min	Max	Increment	Steps
Gas price increase	%	0	0.05	0.001	50
BENG-regulation	n.a.	7	1	1	7
Subsidy	%	0	1.00	0.02	50
Lease-on?	n.a.	False	True	n.a.	2

Supporting information concerning the used dataset

There are multiple ways to look at the adoption rate per separate household group. One could look at the total adoption as part of the total number of households, or one could look at the adoption as a share of the group itself. The former is heavily influenced by the number of households of a certain group in total. The bigger the group, the higher than chance that it will take up a larger share of the total adoption. Therefore, it is chosen to look at the adoption rate as part of the group. In Table 22 for instance, some statistics of the household groups can be seen which are later in the chapter used to explain some results. What can be concluded from the table is that the majority of households in the model are part of the environmentally aware, whereas the faithful environmentalists take up a shy 10% of the total. Also, the gas usage of the unaware energy-users is significantly lower than the groups. As for the income groups, the gas usage increases as with a higher income, and the energy label decreases. The number of households with an income of 1 or 2 is minimal in the model.

Table 22: Statistics of the dataset used in the model. Per household group and income groups.

Averages per household and income groups					
Household Group					
	Income	Gas usage	House type	Energy-Label	Share of dataset
Unware energy users	3,57	1341	1,47	3,38	24,70%
Pragmatic Comfort Seekers	4,87	1673	1,24	2,67	23,30%
Environmentally aware improvers	4,57	1697	1,34	3,93	42,70%
Faithful environmentalists	3,36	1611	1,21	3,77	9,30%
Income groups					
Income 1	N.A.	1512	1,31	4,17	1,80%
Income 2	N.A.	1488	1,34	4,03	3,70%
Income 3	N.A.	1284	1,43	3,73	21,20%
Income 4	N.A.	1417	1,39	3,5	31,66%
Income 5	N.A.	1621	1,30	3,29	21,10%
Income 6	N.A.	2194	1,17	3,24	20,50%
Average for all households:	4,28	1595	1,33	3,49	

7.3.2 Results of the base run

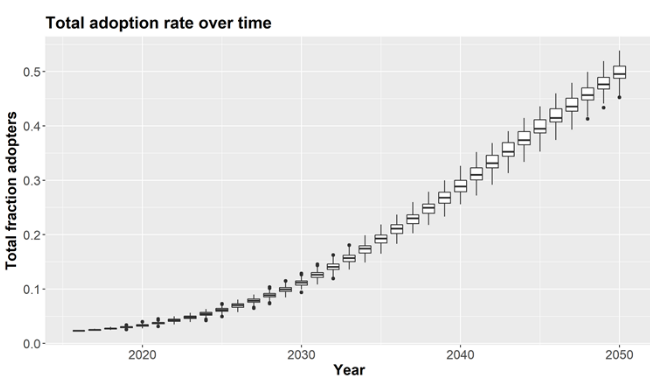


Figure 23: Total adoption over time, base run

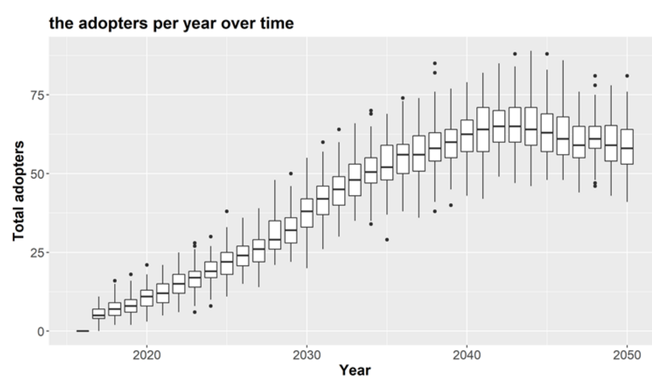


Figure 24: The adopters per year, base run

The variation of the total adoption is low, varying from 55% to around 60%. The beginning of an S-shape curve is visible. In Figure 23 the first half of the bell-shaped curve is visible. The highest number of adopters in a year is from 2038 to 2045, with a median of around 75 households.

Besides the total adoption and the adopters per year, multiple other measures were analysed to gain insight in the detail of the adoption. In Figure 25 for instance, it becomes clear that the HHPs are adopted most often, with ASHP around 5% behind and GSHP slightly behind ASHP. In the first years, ASHPs are ahead of HHP, until 2025, when HHP takes over. As for the household groups, the environmentally aware are most eager to adopt, although the three other groups show a total adoption of more than 50% on average, as can be seen in Figure 26. Not very surprising is the adoption results per income group. The higher the income, the higher the adoption. The highest income groups adopts relatively more than the other groups, which is mostly due to their high investment budget, enabling them to invest in all heat pumps, no matter the costs.

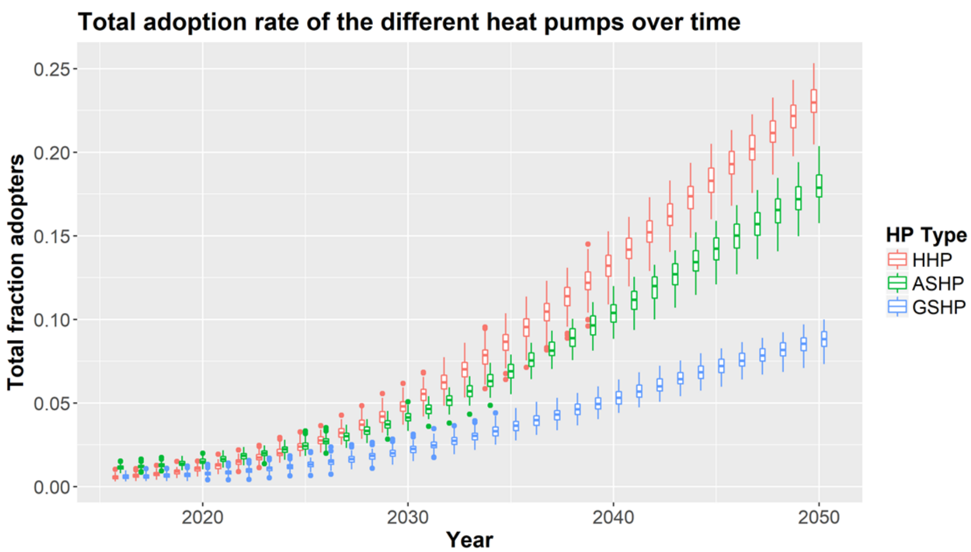


Figure 25: The adoption per heat pump type, base run.

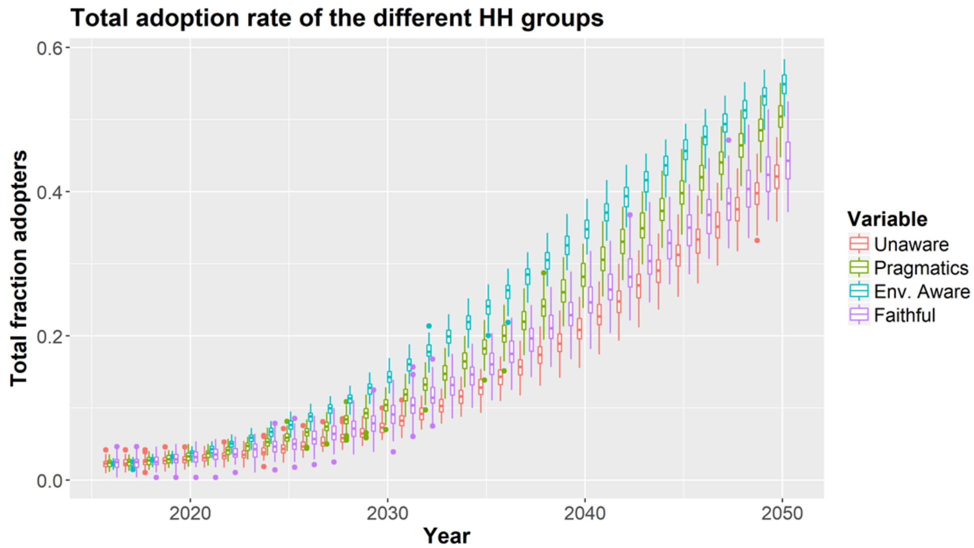


Figure 26: Adoption of the different household groups

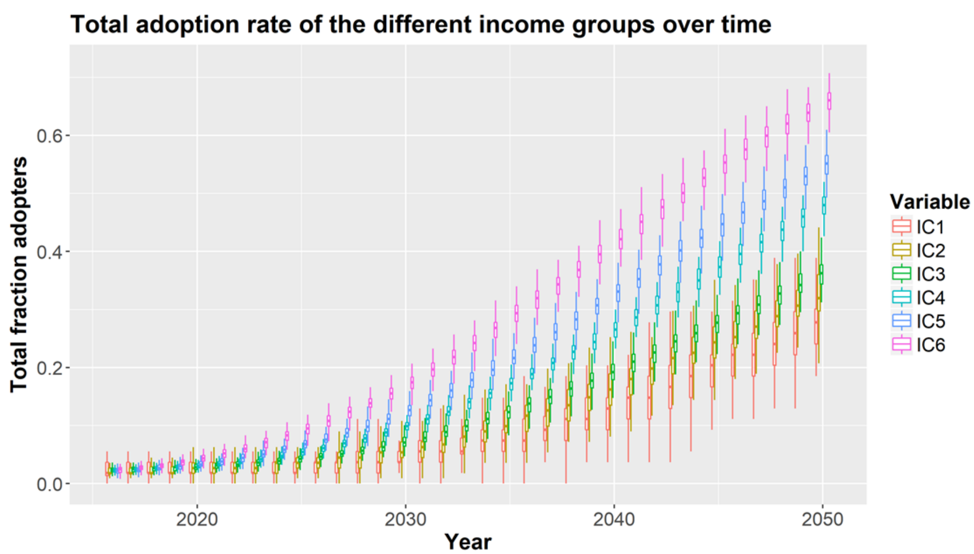


Figure 27: The adoption per income group, base run

The total adoption rate of the energy labels, shown in Figure 28, does not show big differences. The higher variance for household with an energy-label of 7 is due to the low amount of households in that group. The adoption per house type also does not show surprises. Households with house type 1 adopt more on average, as they can install all three heat pump types, whereas house type 2 can only install a HHP or ASHP. Households with house type 1 thus have a higher chance to adopt a heat pump. Figure 30 shows the adoption year of 16 selected households with different characteristics. It should be noted that the number that the household adopted in the 100 repetitions is not included, so some households have more data points than others, most likely the early-adopters. It does however, shed some light on the type of adopters. Is a household an early adopter or laggard? Of the 16 households, four can be described as laggards: HH2, HH6, HH8 and HH10. These households are overall later with adopting a heat pump. The laggards either have a low income, or a low gas usage. Early adopters generally have a higher income and gas usage. Of course the household group, energy label and house type also result in differences concerning the year of adoption.

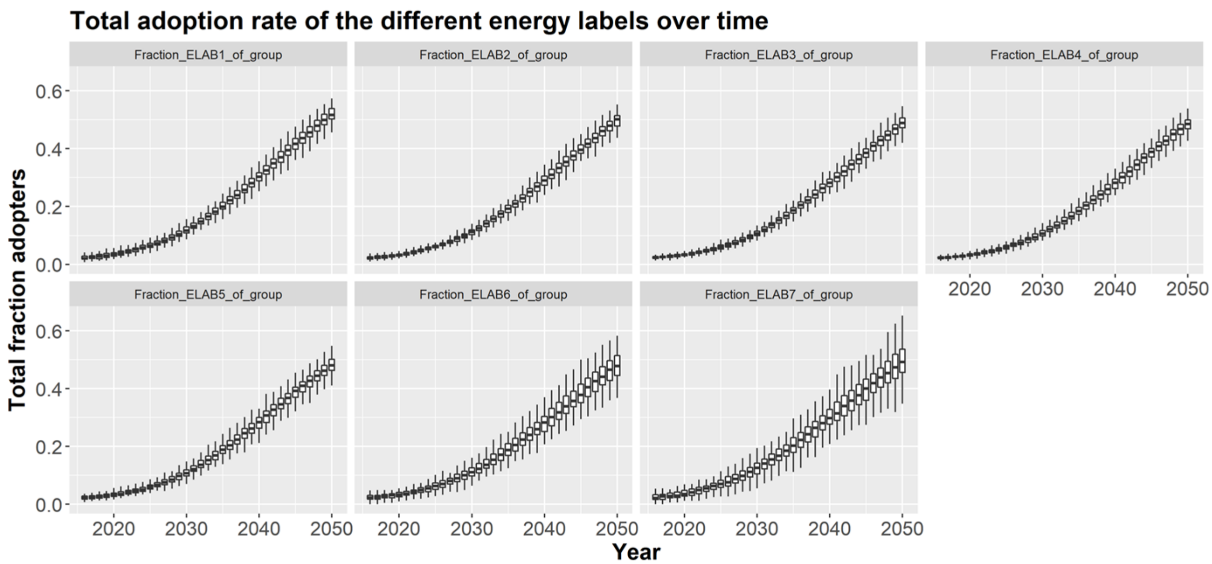


Figure 28: The adoption per energy-label

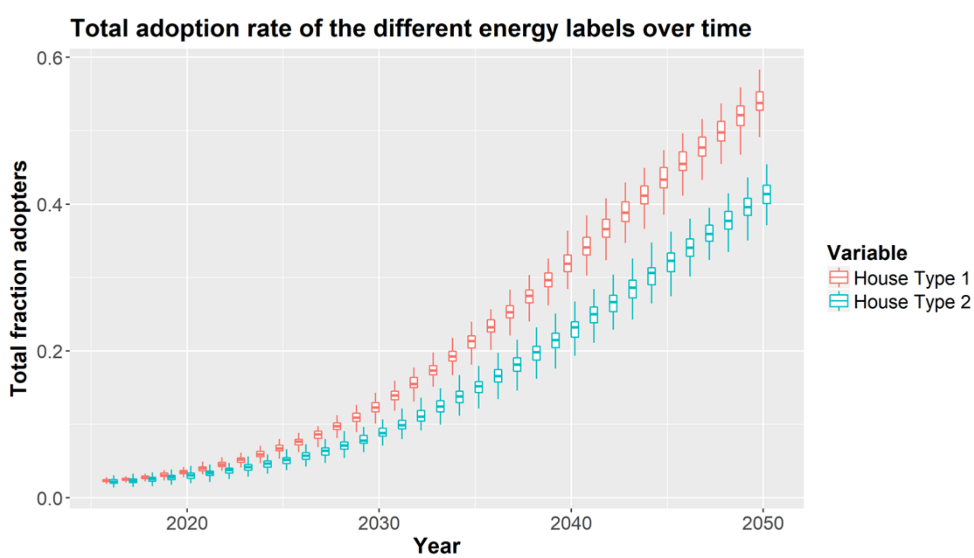


Figure 29: The adoption per house type. Type 2 are apartments and alike. Type 1 is the rest

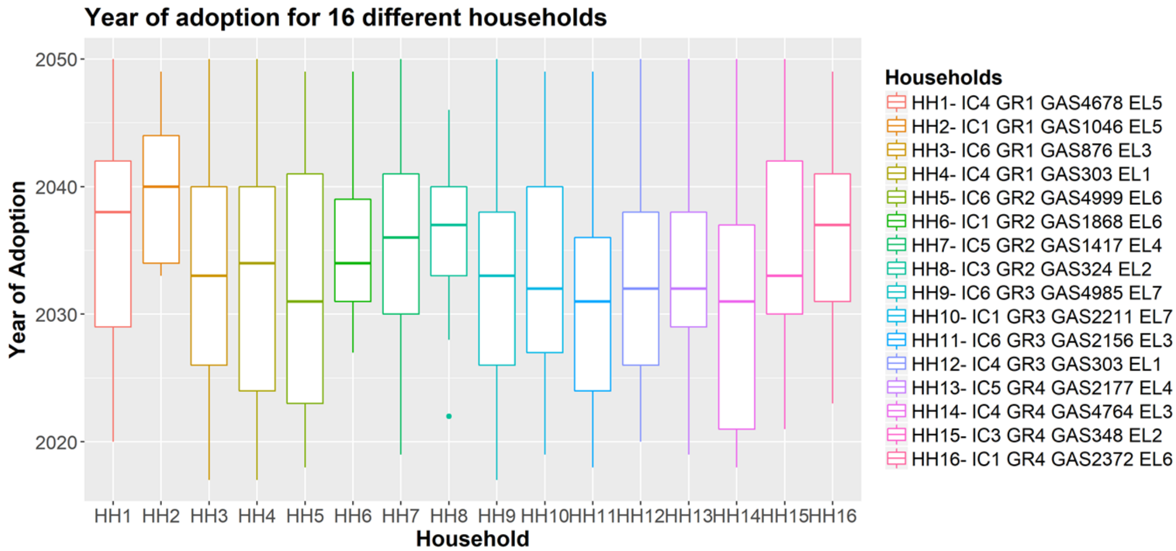


Figure 30: The adoption year of 16 selected households. Their specifics are shown in the legend. IC = income, GR= HHgroup, GAS = gas usage, EL = Energy label.

7.3.3 The lease-or-buy decision

The lease or buy decision has only two values. Either it could be possible for a household to choose between buy and lease, or it could only buy. In the graphs, 'true' means buy and lease is possible, 'false' means only buy.

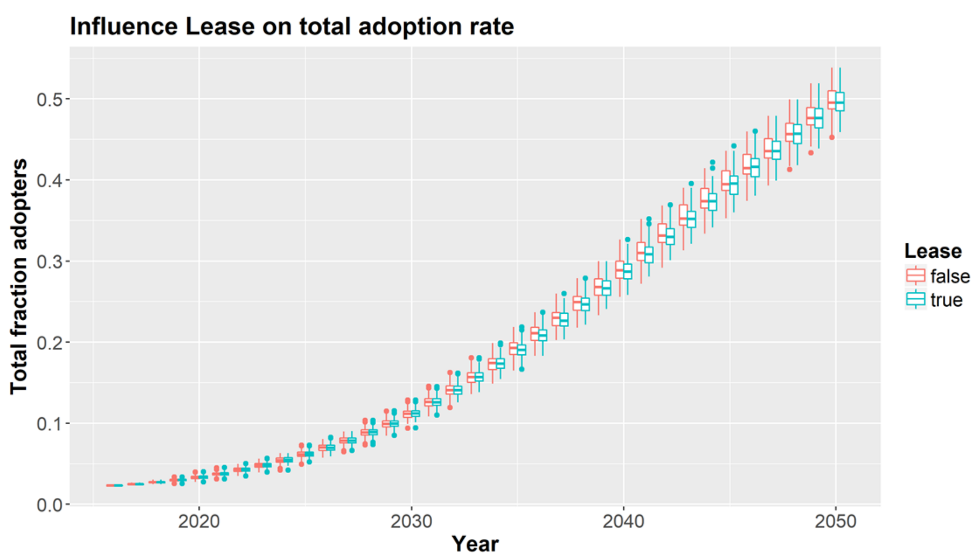


Figure 31: The influence of the leasing possibility on the total cumulative adoption. Lease: false means that there is no leasing possibility. True means that a household can choose between buying or leasing

As can be seen in Figure 31, the possibility to lease a heat pump has little influence on the number of adopters in the model. The overall adoption is only slightly higher when leasing is possible. Also, the variation of the results increases with time, and is slightly bigger for when leasing is true. In the figure one can observe that one year the variation is bigger for *true,* and the next year is this the other way around. The same is true for the upper quartile. Above reasoning is also true for the adopters per heat pump type and household group, see C.1. Therefore, no further plots are shown, as these logically also show little differences. This could indicate that the number of runs is not sufficient for this plot, which is caused by the highly oscillatory nature of the adopters per year.

7.3.3.1 Assessing the lease or buy decision for the complete heating system

The effect of leasing is thus minimal. The reason for this is that that when a household chooses to lease instead of buying, it only affects the investment factor. Also, in the model, it is only possible to lease the heat pump, whereas the total upfront investment cost is also determined by the isolation and LTH costs. This way, the leasing option only influences a part of the investment factor. To assess whether the lease factor can have a more significant effect, another experiment was executed, where leasing was also possible for isolation and LTH. This way, the total investment for a heat pump system can be leased, and thus all upfront costs can be reduced by leasing.

Figure 31 shows leasing all elements of the heat pump system leads to differences between the adoption rates between leasing and when only buying is possible. Both curves show an increasing uncertainty as time advances. Also, the uncertainty is higher for when leasing is possible.

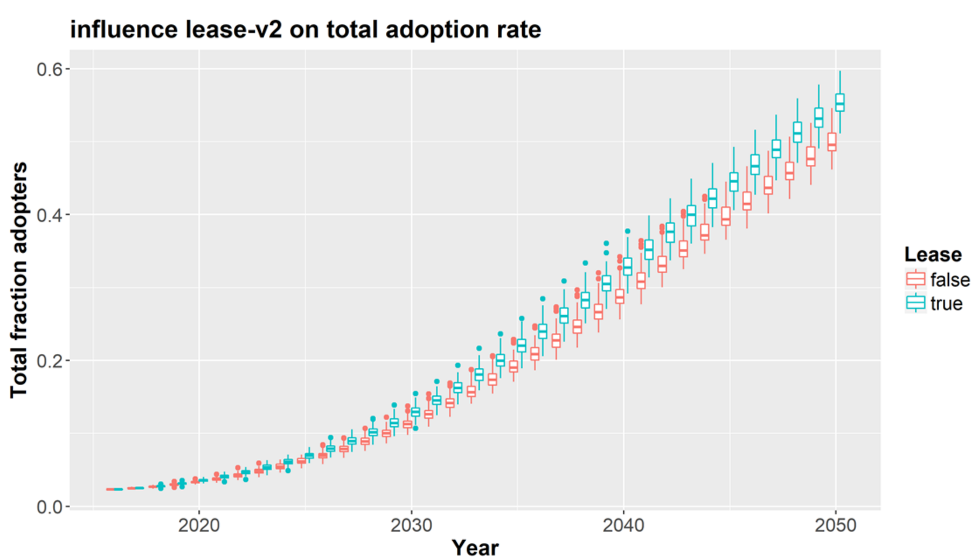


Figure 32: The lease or buy decision for all elements of a heating system. Leave V2 means the new version of leasing.

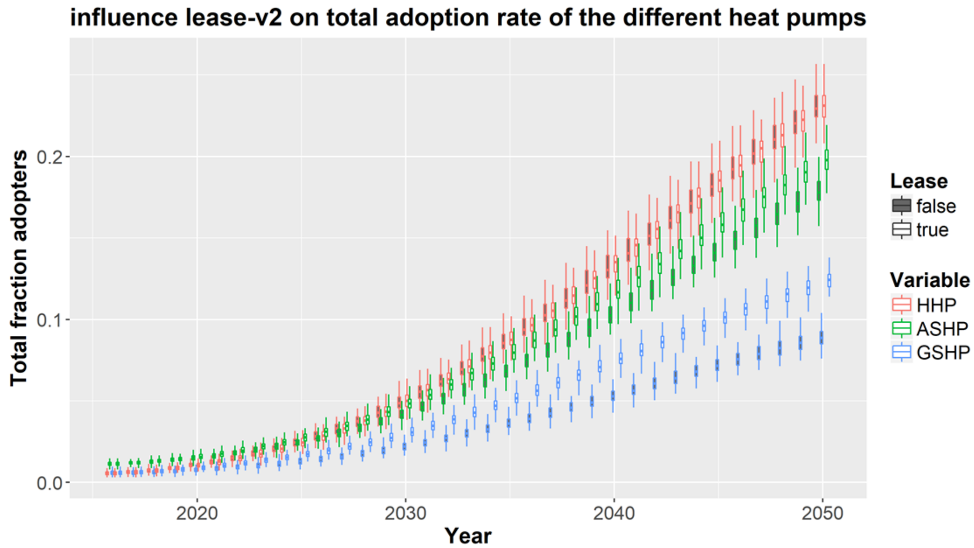


Figure 33: Leasing on complete heating system for different heat pumps.

The adoption per heat pump type also is influenced. ASHPs and GSHPs show an increase of adoption compared to the base situation (Lease = False in the graph), as can be seen in Figure 33. This is because one of the barriers of ASHPs and GSHPs are the high investment costs, which are greatly decreased with leasing. HHPs only improve slightly, as they don't benefit from the lower isolation and LTH upfront costs. Another effect of leasing is on the adoption per income group. The lowest incomes are not affected greatly, as their budgets are still relatively low for any heat pump type whatsoever. As was shown in Figure 33, the hybrids heat pumps are not profiting from leasing. The hybrid heat pumps however, are the type that are mostly installed by the lower incomes (see C.2). Therefore it is not surprising that these incomes are not greatly affected by leasing. On the other side of the spectrum, the higher incomes are also not influenced much. Their budget allows them to acquire a heat pump regardless of leasing, thus it doesn't do much. The income groups that remain, 3 and 4, are mostly affected by leasing. More households in these groups are convinced to buy a heat pump, especially group 3.

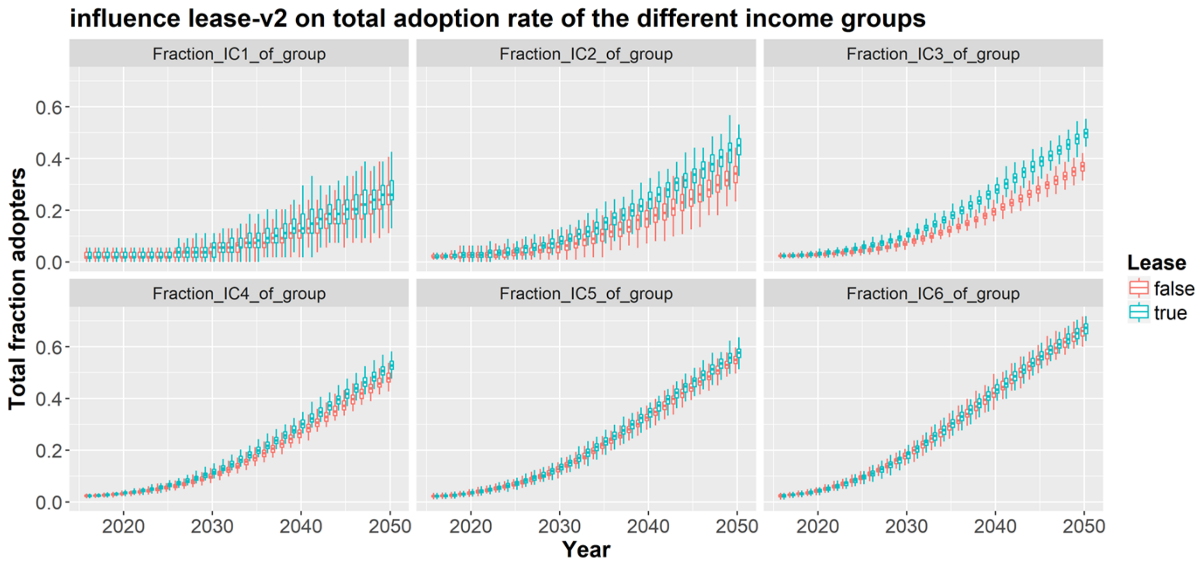


Figure 34: Influence leasing on all elements on the different income groups. False means that leasing is not possible

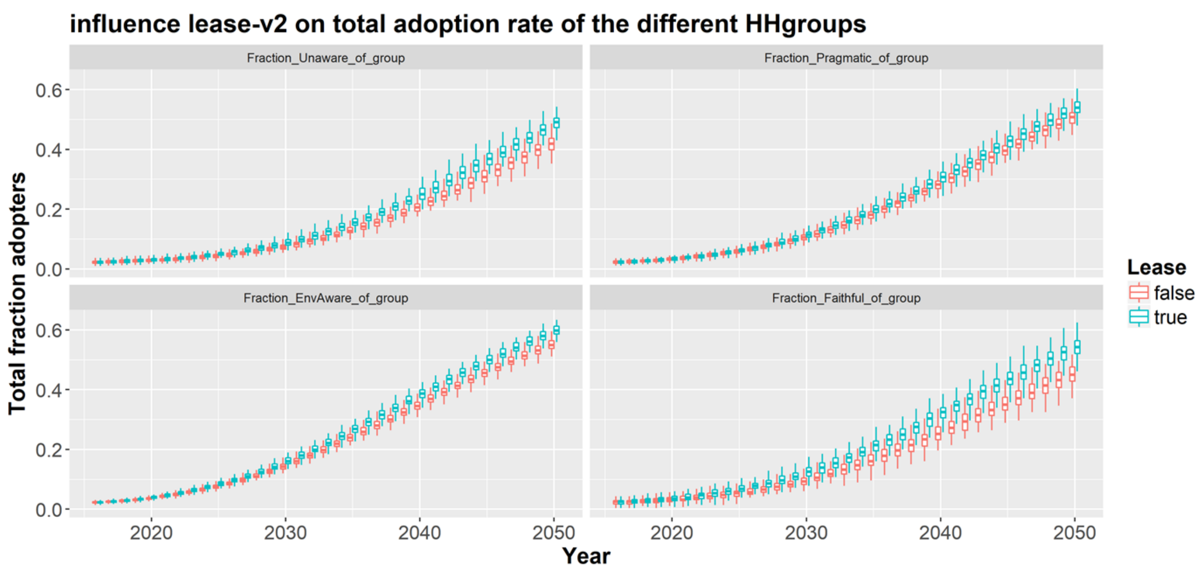


Figure 35: Influence leasing on all elements on the different household groups. False means that leasing is not possible

Per household group

The influence of leasing has most effect on the faithful environmentalists and the unaware energy users, as can be seen in Figure 35. This is explained by their lower average income, and the fact that the lower incomes generally have a lower gas usage, which means less savings (see Table 22 in 7.3).

7.3.4 Influence of the E-label requirement

The energy label requirement was set from 1 (best) to 7 (virtually no requirement). As the influence of the energy-label on the adoption rate is rather small, only graphs with requirement 1 and 7 are shown, as in this way the influence of the requirement can be best evaluated. An energy label requirement 7 could also be interpreted as the base case. Figure 36 shows the results of the total adoption. The uncertainty is low under the base case as well as the highest requirement, while slightly growing as time advances. The influence of the requirement is relatively low on the total adoption rate. The requirement factor is solely determined by the energy label of households. The average energy label in the dataset is 3,49, which means that the requirement factor is on average 0,415 of the maximum 1. The effect on the total intention is thus relatively low. Adding to that is the fact that each year, a number of households improves their energy label, which further diminishes the influence of the requirement. The gradual introduction of the requirement can be seen in Figure 36.

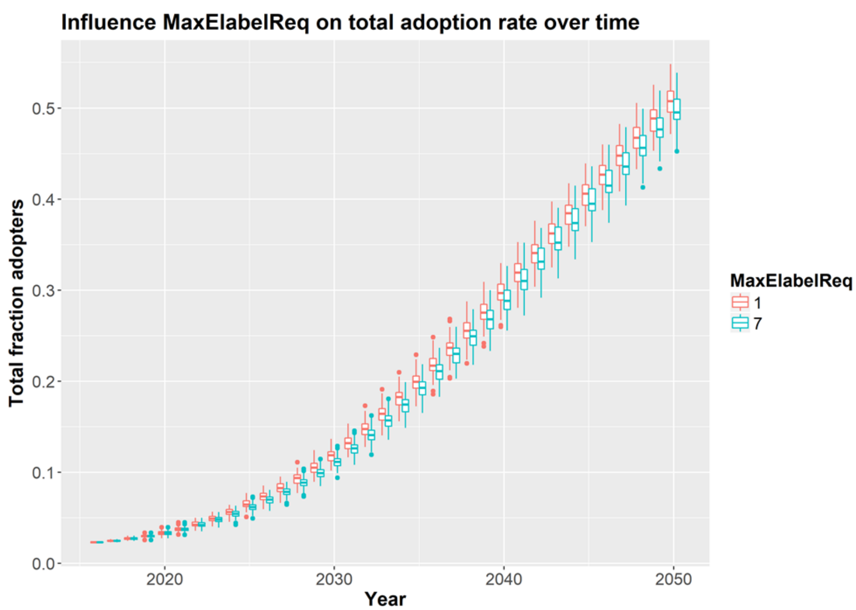


Figure 36: Total adoption rate over time with Elabel requirements 1 and 7.

7.3.5 Influence of subsidy levels

The subsidy level ranged from 0 to 100%, which thus sets the subsidy level for the entire simulation. In Figure 37, one can see that the subsidy has no influence on the emergent pattern (e.g. it is still an S-curve). It does however, have a reasonable effect on the growth of heat pump adoption. The highest subsidy levels reach almost 80% adoption in some runs, where no subsidy is around is closer to 45%. As can be expected, the highest subsidy levels lead to the highest adoption rates, shown in Figure 37. For the rest of the paragraph the base run (20% subsidy) and full subsidy (100%) are used, as such differences clearly show the influence and it improves the visibility of the plots.

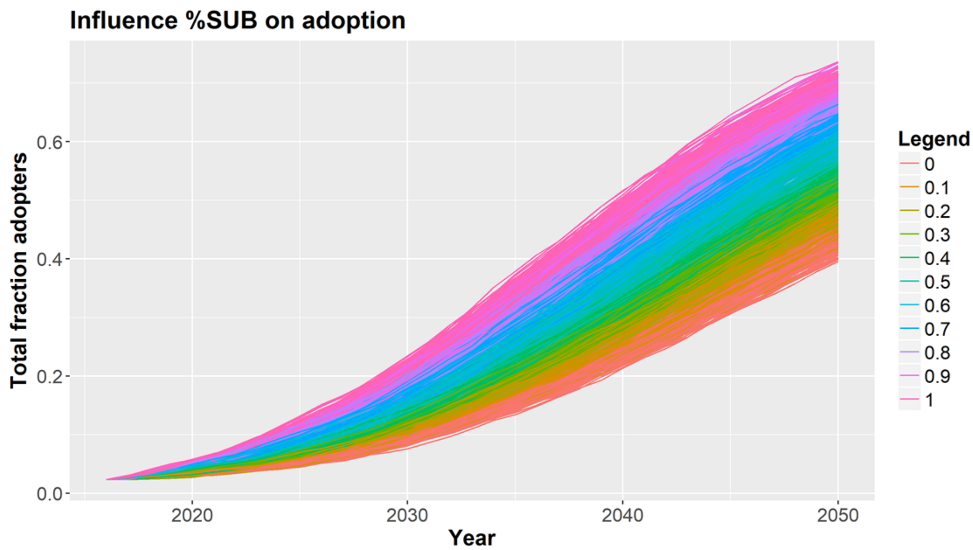


Figure 37: The total adopters over time under different subsidy levels. The values in the Legend are percentages.

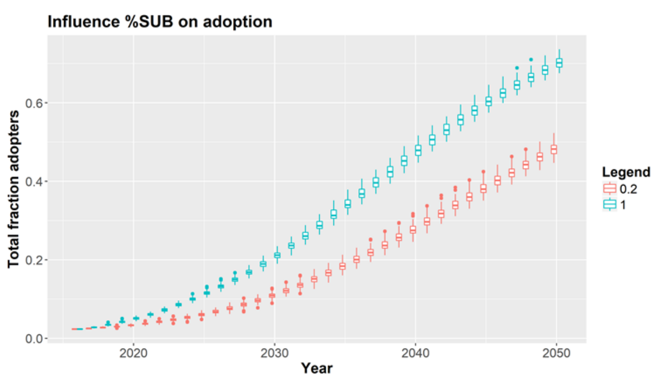


Figure 38: Total adoption over time, Sub vs base

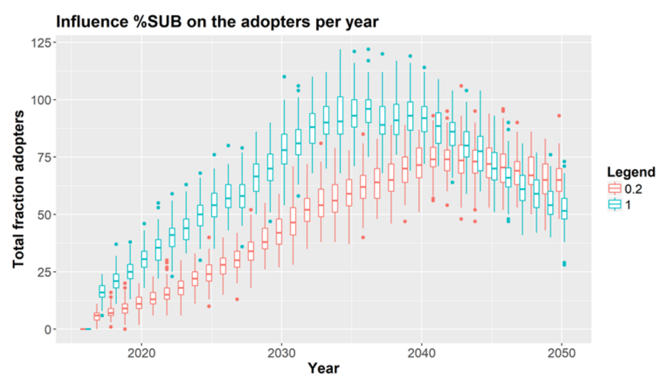


Figure 39: The adopters per year, Sub vs base

High subsidy and the Adopters per year

In Figure 40, the adopters per year are visualized. Overall, these results are not very surprising. The variation of adoption is much higher with different subsidy levels. It is visible here that in the base case, the adopters per year is lower until 2046. After 2046, the median of the base case boxplots is higher than the complete subsidy range. This is because most values in the range 0-100% are higher than 20% and a higher subsidy leads to more adoption in the model. What can be concluded from the figure is that the bell curve reaches its peak earlier overall for higher subsidy levels than the base case, which is why the median of the base case is higher after 2046.

High subsidy and the Adoption per heat pump type

In Figure 40, the influence of subsidies is clearly visible on the effect of the heat pump types. Instead of a situation where HHPs are dominant in the base case, with 100% subsidy all heat pumps are more or less installed in equal amounts. ASHPs are even adopter more than HHPs. Similar to the leasing construction, the subsidy removes the investment cost barrier for the expensive ASHP and GSHP, making them more attractive for households. HHPs are already cheaper, so the effect is less strong.

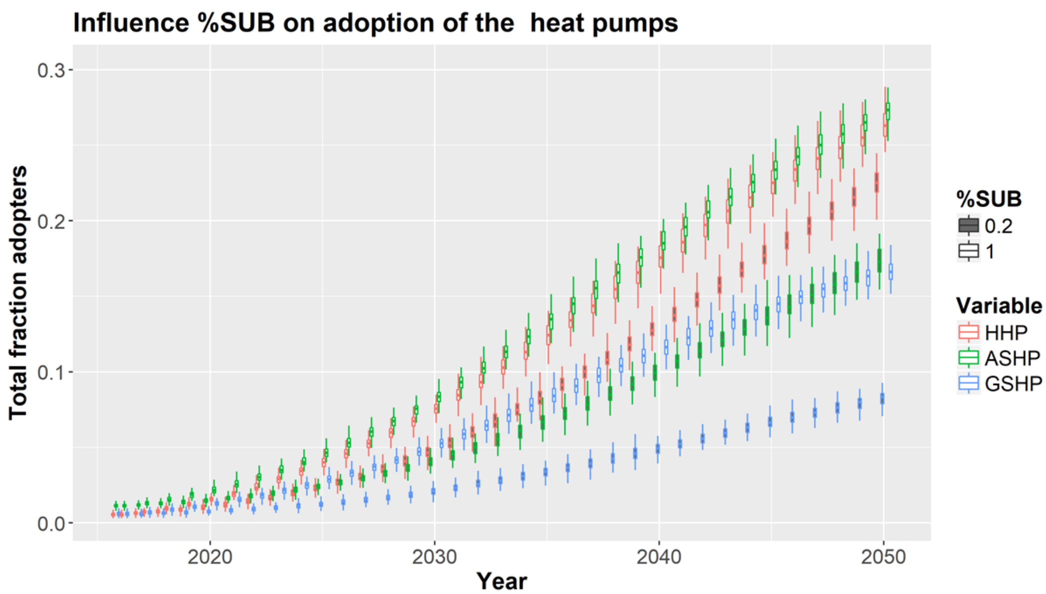


Figure 40: Comparison of the adoption per heat pump type for a high subsidy compared to the base case

High subsidy and the Adoption per level of income

First observation that can be made at the plots of the adoption per income level (Figure 41) for the different levels of income is that lower income have a higher variance compared to higher incomes. This is due to low number of households with low incomes. Another observation is that although all income groups profit from a higher subsidy, overall the higher the income, the lower the effect of the high subsidy. This because the higher incomes are less dependent on such measures. They budgets allow them to install heat pumps mostly regardless of a subsidy.

Adoption per house type and per household group

One interesting aspect in Figure 42 can be observed. The unaware energy users are mostly influenced by the subsidy incentive. Their adoption rate in total is almost 25% more than in the base case situation, judging by the median value. Other household groups also adopt around 20%. The reason the unaware adopt show a slight higher growth in adoption originates in their preferences. They value the payback time highly, higher than the other groups. With a subsidy of 100%, the payback is 0 years, leading to a maximum payback value in the decision module.

Adoption per energy-label and house type

The effect of high subsidies was also analysed on the energy-label and house type. With 100% subsidy, the households with a house type 2 relatively adopted more heat pumps compared to the household with house type 1. This is likely caused by the lower average income of house type 2 (see Table 22). There was no noticeable difference concerning the adoption of different energy labels with a high subsidy.

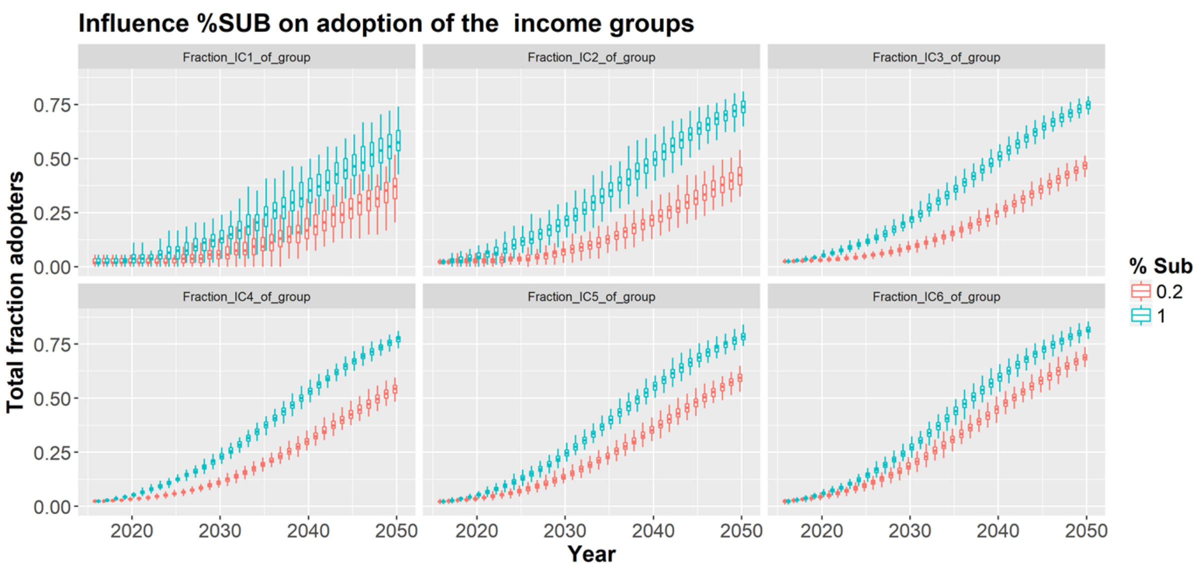


Figure 41: The influencing of a high subsidy on the adoption of the six income groups. Income 1 is on the op left. The highest income 6 is bottom right.

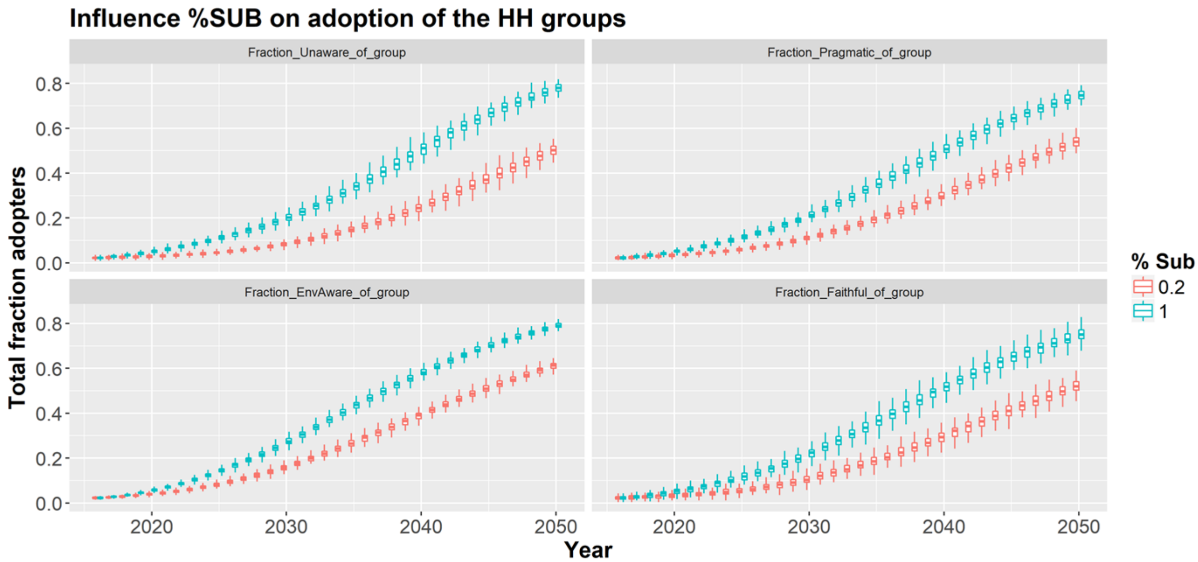


Figure 42: Influence of the subsidy on the adoption per household group

The adoption year of 16 selected households

That household are generally quicker to adopt, was shown with the adopter per year. It is supported by the adoption year of the 16 selected households. The households with the lower incomes adopt earlier overall. Households that can normally be described as laggards are now among the majority (HH2, 6 and 10). The environmentally aware (group 3) with a high income do not show much difference in adoption year.

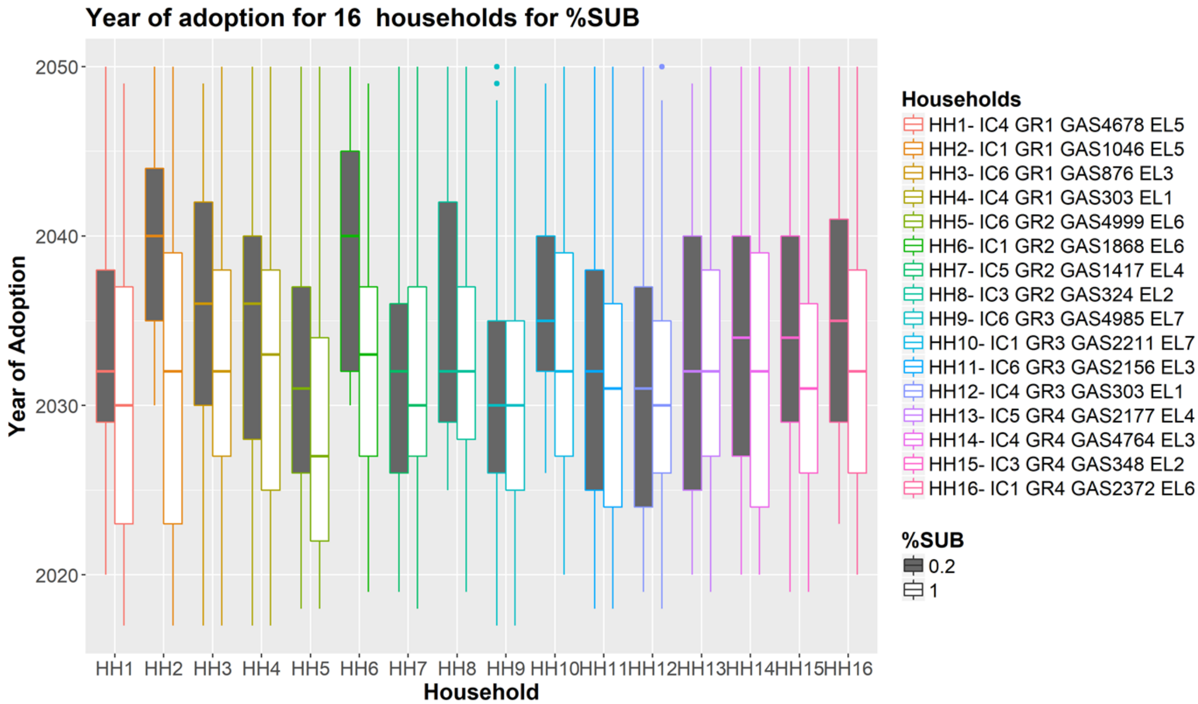


Figure 43: The year of adoption for 16 different households. High subsidy (1) versus the base run (0.2)

7.3.6 Influence of gas prices

Just as the subsidy, lease and energy label requirement, different gas price growth rates have no influence on the adoption pattern of the model, as is shown in Figure 44 and 45. Diverse gas growth rates have a significant influence on the overall adoption rates. Also, the higher the gas price growth rate, the higher the overall adoption rate will be. The overall adoption rate with a gas price growth rate of 5% leads to around 10% more adoption in 2050 under compared to a growth of 2%. The difference is thus not as high compared to a high subsidy.

High gas price growth rate and the Adoption per heat pump type

The adoption of the three heat pump types is different for a high gas price growth compared to a high subsidy. The popularity of the heat pumps is not becoming more equal. Instead all heat pump types are more adopted. The gas price is implemented in such a way that it only influences the savings factor. One would expect that the hybrids would not be as popular with a high gas price, as the gas boiler in the hybrid system uses gas. However, the heat pump provides the majority of the heat. So compared to a situation with solely a gas boiler, a HHP leads to sufficient savings. So although the savings per year of an ASHP or GSHP are higher, this difference is not large enough for households to switch to a non-hybrid heat pump.

High gas price growth and adoption per HHgroup, income group, energy label and house type

There were no differences found in the adoption within the different income groups, different energy labels, house types or household groups.

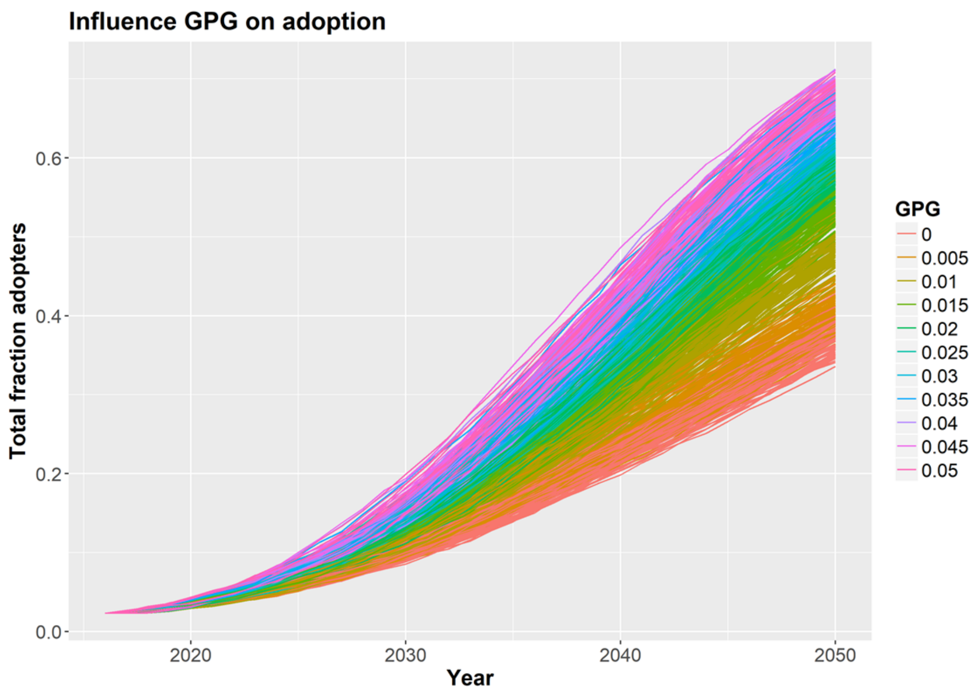


Figure 44: Total cumulative adopters over time for the range of gas price growth rates for all included gas prices. GPG = Gas Price Growth

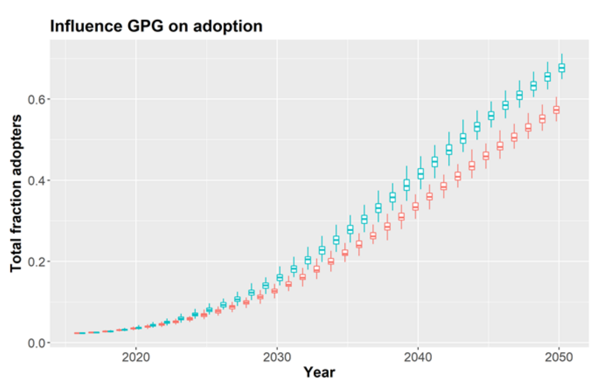


Figure 45: Total adoption over time, GPG vs base

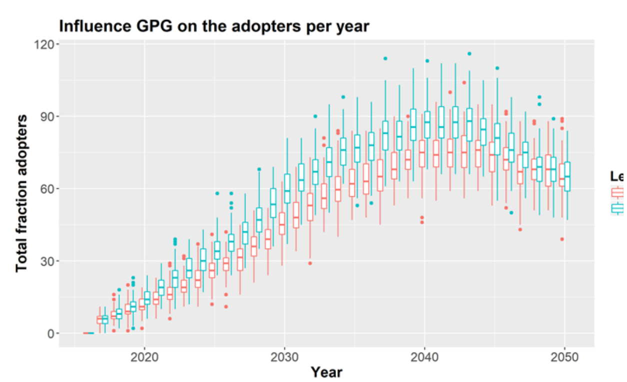


Figure 46: The adopters per year, GPG vs base

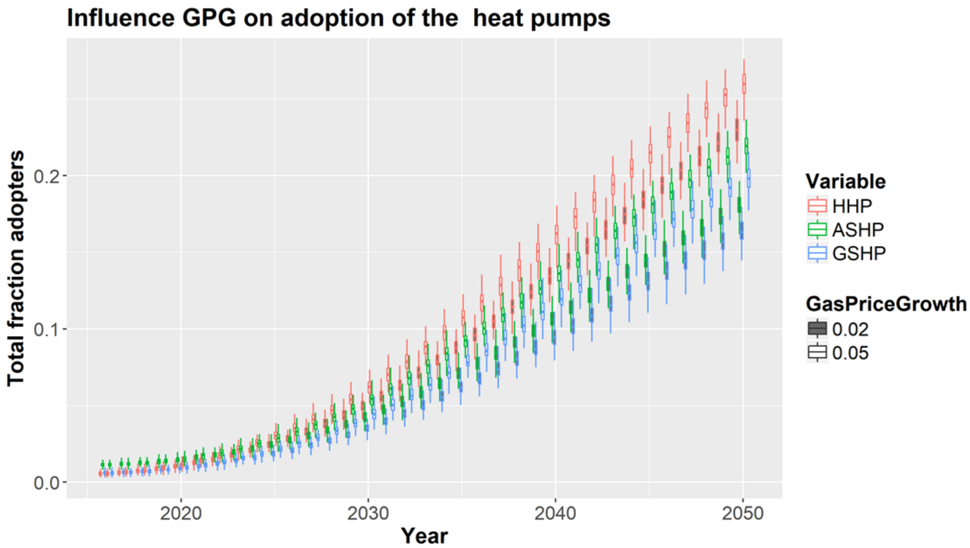


Figure 47: The adoption per heat pump type with 5% GPG and the base case (2%)

7.4 Scenario exploration with the gas price growth rate and subsidy

Within the parameter space, scenarios can be identified. When the governmental measures BENG regulation and subsidy are combined to *government policy* this leaves the following scenario space, plotted on two axis, seen in Figure 48. In the model, the possibility to lease is either on or off, which means there are only two options. With grey government policy is meant that there are no subsidies and no BENG-requirements, while green means strict BENG requirements and high subsidy levels. The scenarios described by DELTA (2012) can be placed on the scenario space in Figure 48. One can see that the quadrants where 4 and 5 are placed are not taken into account. Whether the scenarios 4 and 5 are likely to happen or not, they should still be part of the scope, as the emergent behaviour of the model could be lead to interesting results in these quadrants.

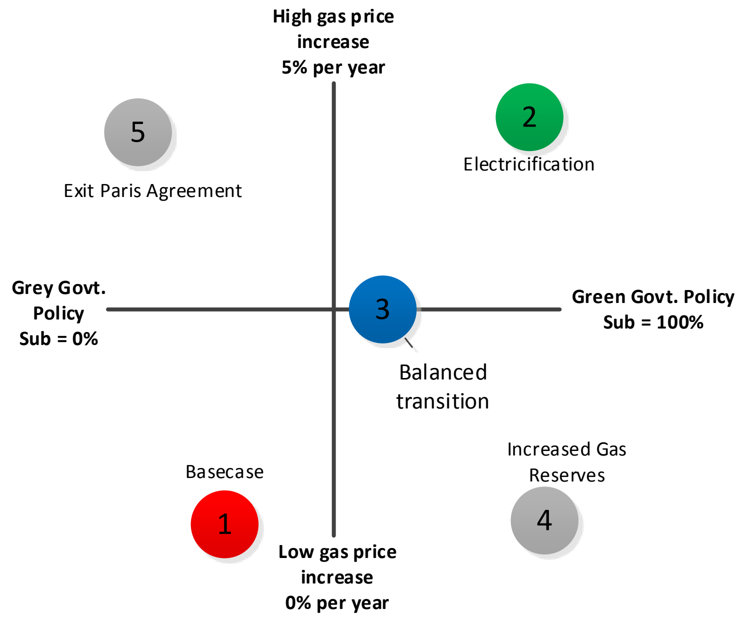


Figure 48: The scenario space of the financial incentives for subsidy and the gas price

Combining the scenarios by DELTA (2012) with the parameters of the model leads to the following descriptions for scenarios 1 to 3. Scenario 4 and 5 are based on Figure 48.

Scenario 1: Customer choice. The customer choice scenario is the baseline scenario, meaning current regulations are in place, and the gas price increase is relatively low. The subsidy is thus also low.

Scenario 2: Electrification. In the electrification scenario, prospects are better for heat pumps (mostly ASHP and GSHP), meaning both the gas price increase rate and subsidies are high.

Scenario 3: Balanced transition. In the balanced transition gas prices increase more than the *customer choice* scenario, but not as much as the electrification scenario. Similar arguments are true for the subsidy.

Scenario 4: Increased Gas reserves. In this scenario, the gas price increase per year is very minimal. Possible due to increased supply, therefore the scenario is called increased gas reserves. The government still aims to increase the adoption by subsidizing large shares of the total investment.

Scenario 5: Exit of Paris agreement. The government does not provide much subsidy for heat pumps in this scenario, thus it does not aim to fulfil the requirements of the Paris Agreement. The gas price increases with a high growth rate each year.

7.4.1 Exploring the scenario space

Separately the parameters lease, energy label requirement, subsidy and gas price growth thus do not have a significant effect on the general pattern. Lease and the energy label requirement do barely have an impact at all. Therefore, it is chosen to continue solely with the gas price and subsidy levels. The ranges of the gas price growth and subsidy are shown in Table 23.

Scenario	**Gas price growth (%)**		**Percent subsidized (%)**	
	Low	High	Low	High
1: Customer choice (CC)	0	1	0	20
2: Electrification (EF)	4	5	80	100
3: Balanced Transition (BT)	2	3	50	70
4: Increased gas reserves (IGR)	0	1	80	100
5: Exit Paris Agreement (EPA)	4	5	0	20

Table 23: Settings scenarios for the gas price growth and the percent subsidized

The results are shown in the figures Figure 49 and Figure 50. Unsurprisingly, the customer choice scenario has the lowest cumulative adoption. Also the pattern seems to have a more linear growth, instead of the beginning of an S-curve. The higher the total cumulative adoption, the more the S-shaped curve is visible. Another observation is the low discrepancy in the *Electrification* scenario. When the subsidy is thus high, and the gas price growth per year is high, the possibility that households adopt a heat pump is considerably higher. All other scenarios show more uncertainty.

Comparing the *Exit Paris Agreement* and *Increased Gas Reserves* scenario shows whether the gas growth per year or the subsidy level has more influence on the total adoption. It can be concluded that when the subsidies are 80% or more (IGR scenario), the total cumulative installed heat pumps is higher than when the gas price increases with 4 to 5% every year (EPA Scenario). This is supported by the fact that the *Balanced Transition* scenario also leads to higher heat pump adoption than the *Exit Paris Agreement* scenario.

The adoption year of the different scenarios

The effect of the subsidy and gas price incentives is also clear when looking at the adoption year, seen in Figure 51. In the *Customer Choice* scenario, there is a difference between early adopters and the late majority or laggards. In the *Electrification* scenario, this difference is very little. For some households, the incentives have little effect. For instance household 11. Its year of adoption is generally the same in each scenario. The incentives thus don't stimulate the early adopters or innovators to adopt even quicker, but it is mostly helping the early majority, late majority and laggards.

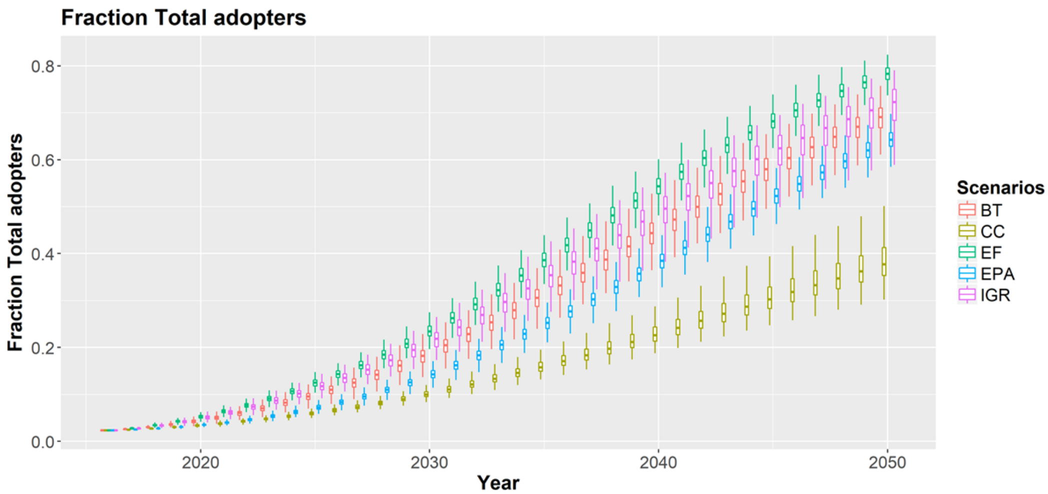


Figure 49: The cumulative total adopters over time for the five scenarios. The sequence of the boxes is according to the scenarios in the legend on the right.

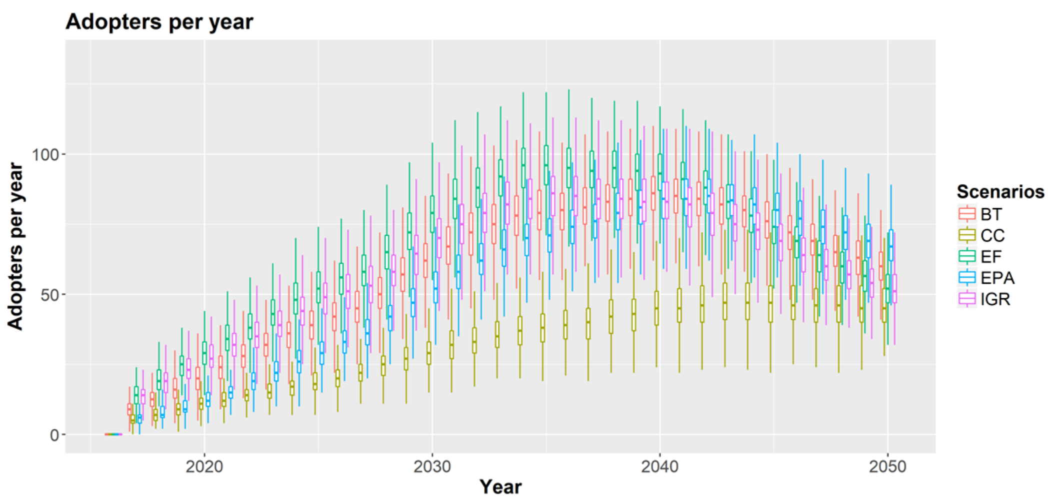


Figure 50: The adoption rate per year for the five different scenarios. The sequence of the boxes is according to the scenarios in the legend on the right.

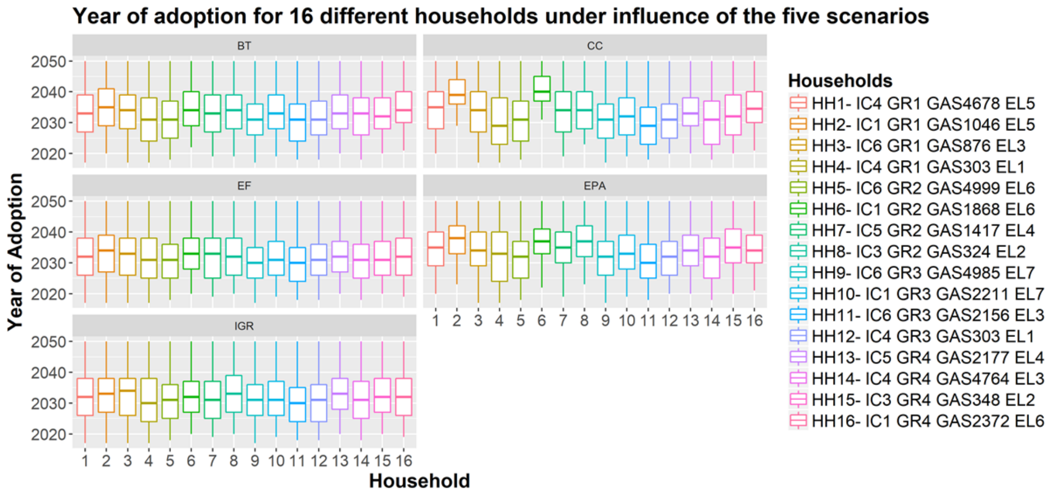
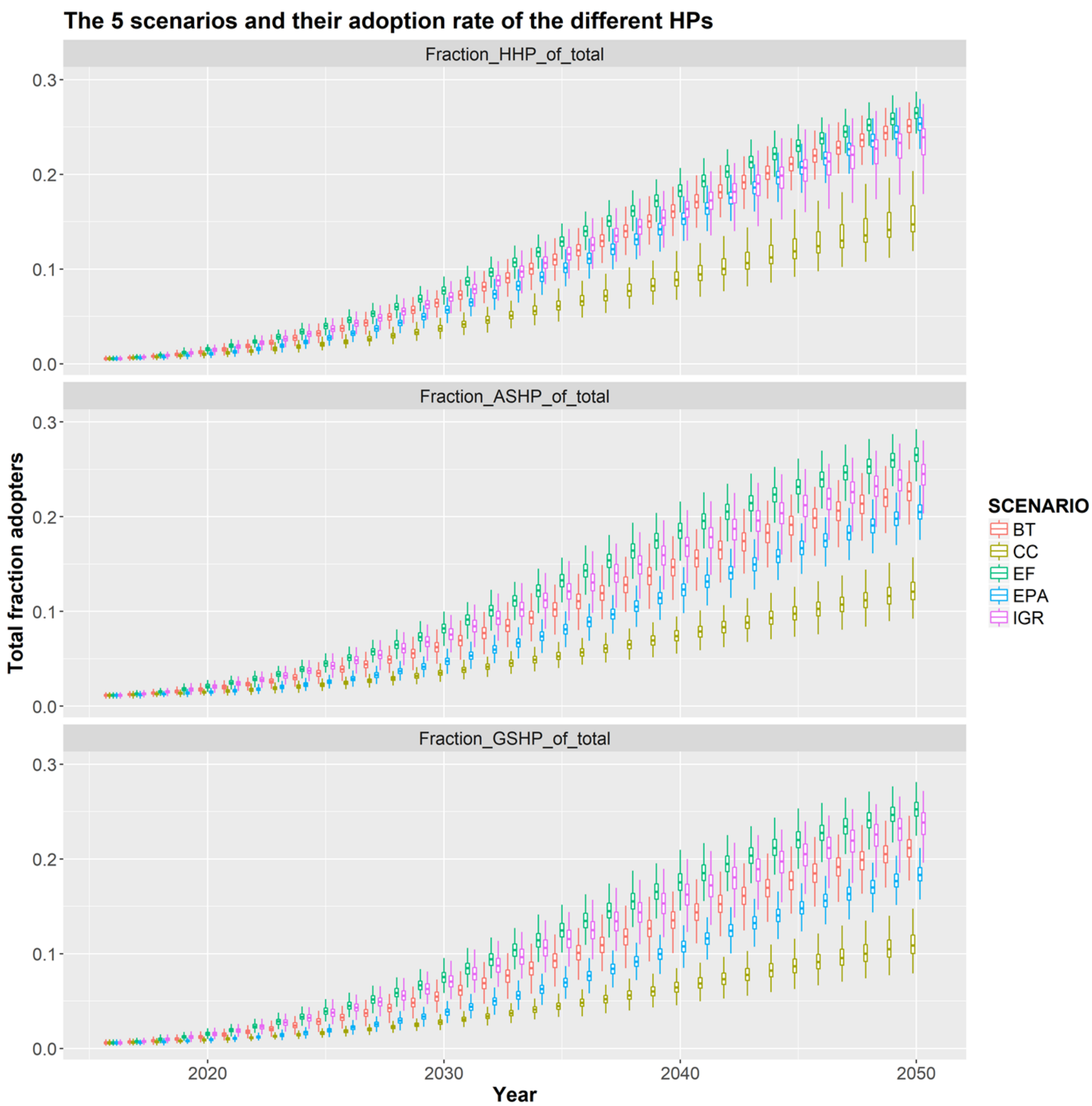


Figure 51: The adoption year of 16 selected households for the five scenarios

The scenarios and the adoption per heat pump type

Around 25% of households adopt a heat pump in four of the five scenarios. For ASHPs and GSHPs, the difference is larger for these four scenarios. From the scenarios it can be concluded, that if a situation with more ASHPs and GSHPs is preferred, the focus should be on high subsidies. The adoption of ASHP and GSHP is highest in the scenarios with a high subsidy, *Electrification* and *Increase Gas Reserves.* The balanced transition scenario even leads to more hybrid heat pumps overall compared to the *Increase Gas Reserves* scenario, where the gas price is very low. The adoption of heat pumps per scenario can be found in Figure 81 in Appendix C.5.



7.5 Experiments with discontinuities: Temporary subsidies and gas prices

The main conclusion that can be derived from the previous experiments is that both the gas price and subsidy have a big influence on heat pump adoption. As the results are rather straightforward, some more exploration into the models behaviour was necessary to assess the usefulness of the model. Firstly, it was examined what influence a short spike in subsidy levels or gas price would have on the adoption of heat pumps. It could be a realistic situation, where the government needs to achieve government goals before a certain deadline. This is presented in 7.5.1. The chapter continues with a subsidy budget, which is the situation as of now with the

ISDE (see 3.4.2.1). Both a fixed and dynamic budget were examined, discussed in 7.5.2. Finally, the situation is explored where a high subsidy level for a certain period also influence the awareness and reason for households, which if found in 7.5.3.

7.5.1 DISC-A: A sudden in subsidy levels or gas price for 1 to 5 years

Besides the goals for CO_2 neutral low temperature heating 2050, governments have multiple temporary goals. In the new government agreement for instance, the goals is to have 49 percent less CO_2 emitted in 2030 compared to 1990. This experiment assumes the situation where the year is around 2025 to 2029 and that 49% is not possible with the current policy. Then the government increases the subsidy or gas price drastically for a few years, to lower them to normal values after 2030.

Settings of the experiments

The duration of the incentives vary between 1 and 5 years. As 5 years provided the most clear differences with respect to the base case, this duration was selected. The starting year of the measure was also varied with steps of 5 year from 2020. The subsidy starts at 20% and is 100% in during the spike. The gas price is set on whatever the price is at that point and the spike is set on 2 euro per m^3.

Tabel 1: settings of the experiments for temporary gas prices and subsidy

Variable	Lower bound*/normal value**	Upper bound*/spike**	Increment
Duration	1*	5*	1
Starting year	2020*	2045*	5
Percent Subsidized	20%**	100%**	N.A.
Gas price growth	Price at timestep**	2 euro/m^3**	N.A.

Results of a high subsidy and high gas price for 5 years with a start in 2020

In Figure 52, Figure 53,Figure 54 and Figure 55 the results of the experiment can be found. For both gas and subsidy, the adopters per year during the spike are 15 to 25 adopters per year higher. This results in a small bump in the S-curve for the total fraction adopters over time (Figure 52Figure 54). The reason that these drastic incentives only results in a relatively small bump is caused by the number of adopters that are evaluating heat pump adoption, which is determined by the awareness of households and whether they have reason. A difference between subsidy and gas is that subsidy not only results in more adoption during the incentive, it also has a long term effect on the total adoption. In 2050, the total adoption is higher compared to the base case, whereas with a high gas price growth rate, the adopters per year is lower than the base case after the duration of the incentive has passed. This due to the way it is implemented. After the incentive, the gas price returns to the price it was before the incentive. In the base run, the gas price increases every year, so in 2026, the gas price is higher in the base run compared to the incentive. This effects both the savings and the payback time, and thus the intention of the households.

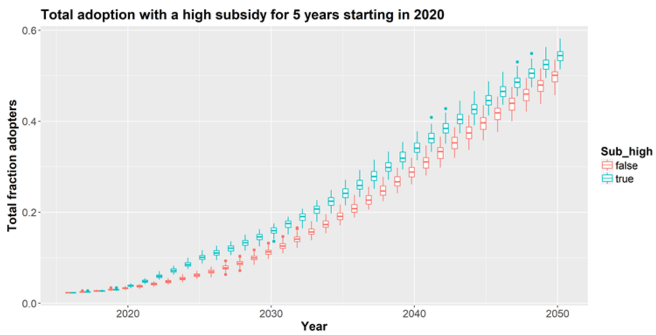


Figure 52: Total adoption over time, sub spike vs base

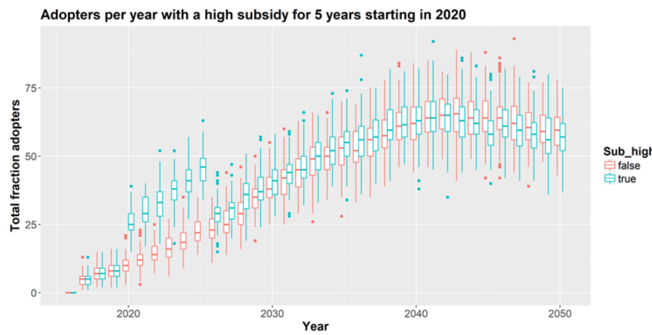


Figure 53: The adopters per year, sub spike vs base

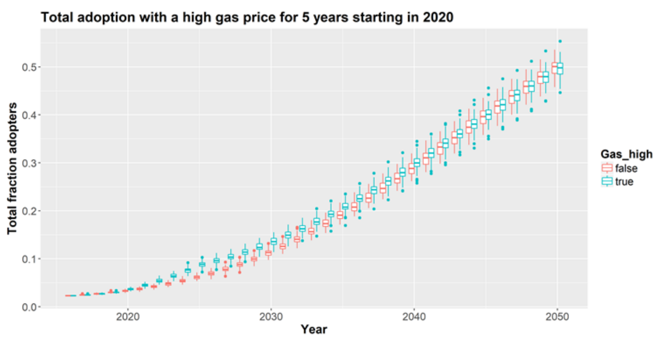


Figure 54: Total adoption over time, gas spike vs base

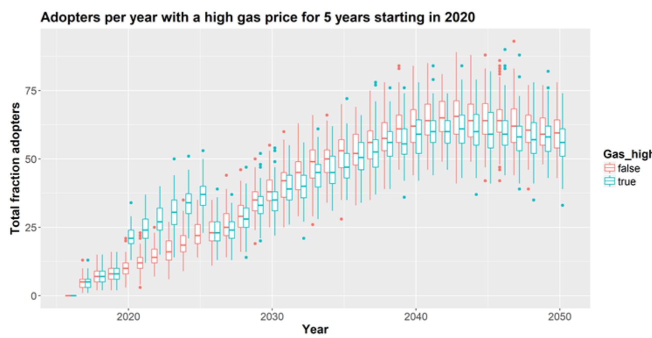


Figure 55: The adopters per year, gas spike vs base

7.5.2 DISC-B: A dynamic subsidy budget

So a fixed increase in the percentage subsidised or the gas price improves the adoption in the short term, but it has little or no effect on the long term. What about a subsidy budget? In all the experiments so far, an infinite subsidy budget was assumed. In reality, governments work with budgets. If that budget is empty, the subsidy stops and remaining potential adopters either have to wait or invest without subsidy. Therefore two experiments were performed with a budget. The first experiment used a fixed budget for the entire period. The second based its budget and subsidy level on the adopters per year.

This subsidy budget is thus dynamic. Both the height of the subsidy as the budget adapts dependent on the adopters per year. The percent subsidised and subsidy budget are matched. 10% subsidy is matched with €50.000,- subsidy budget. The assumption is thus made that the higher the percent subsidised, the higher the needed budget. The subsidy changes based on two statistics. If the adopters per year is lower than 50, the subsidy is increased with 10% and the budget with €50.000,-. The maximum is thus 100% and €500.000,-.

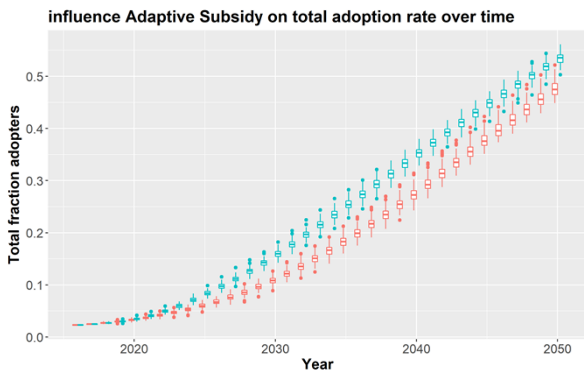


Figure 56: Total adoption over time, DISC-B. False means the base situation

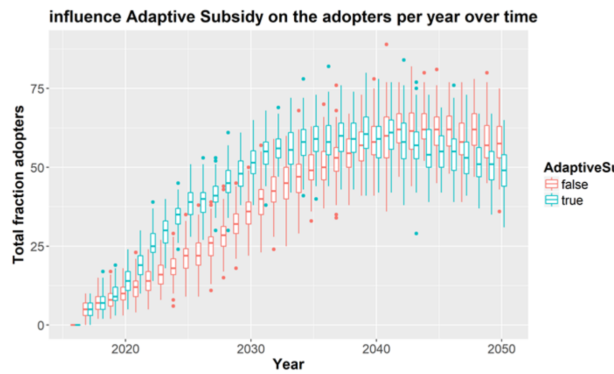


Figure 57: The adopters per year, DISC-B. False means the base situation.

As can be seen in Figure 57, the adopters per year is lower than 50 until 2030, which means the subsidy increases from the initial 20% to the maximum, as well as the budget. From 2030 the adopters per year is sufficient and the subsidy decreases. It is difficult to estimate the effect of the adaptive budget and percent subsidised. The growth of the adopters per year decreases from 2030 onwards, however, this cannot be solely described to the budget. It does seem that the adaptive subsidy budget has a different behaviour. It has the beginning of an S-curve, however, it seems to have a more steady growth compared to the base case. One would expect this measure to stabilise the adoption per year. First it should increase to the value of 50 adopters per year, afterwards it should decrease the subsidy until the adopters per year are lower than 50 to increase the subsidy again. From the figures it cannot decisively be concluded if this is the case.

7.5.3 DISC-C: A change in awareness and reason due to subsidy increase

Until now, it has been assumed that a high subsidy has no influence on the awareness or reason of households. In reality however, it could be argued that the information of a high subsidy is available will disperse quicker among households. Furthermore, it could also convince households to invest quicker, or with other words, they have a reason to adopt quicker than usual, because know is the time to get a good deal on a heat pump system. Whether such government measures are realistic is doubtful. Providing 100 percent subsidy for all household would simply be impossible to fit within government budget. On the other hand, one could pose the hypothetical situation that at some point the government needs to reach its climate goals, or it will be penalized by for instance the EU. The point here is that the experiment posed here might be extreme, but such situation are not entirely unthinkable. Furthermore, this experiment can specifically show why the ABM model is useful. In Table 24, the variables are presented. The duration is 1, 2 or 3 years. The starting years is also threefold with either 2020, 2040 or 2050 and the awareness increase is either 1, 2 or 3. This means that during the measure the awareness-value is increased, thereby resulting in a higher chance that a house becomes aware. The reason chance is set on 25%, which means each household has a 25% chance that is has a 'reason'. When the duration is three years, the households thus has three chances to become aware and have reason.

Table 24: Setup of variables for the DISC-C experiment.

Variable	Lower bound	Upper bound	Increment
Duration	1	3	1
Starting year	2020	2040	10
Awareness Increase	1	3	1
Reason chance	25%		

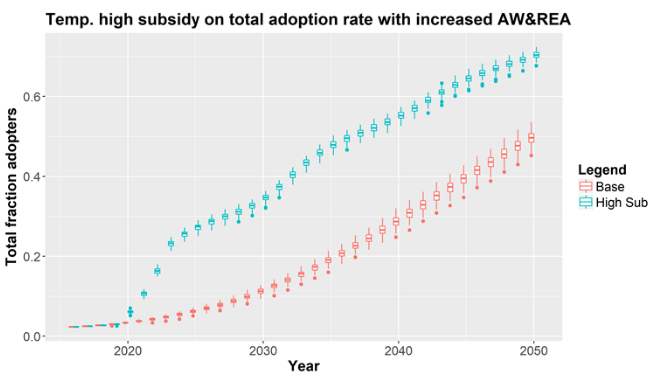


Figure 58: Total adoption over time, DISC-C. AW = Awareness, REA = reason

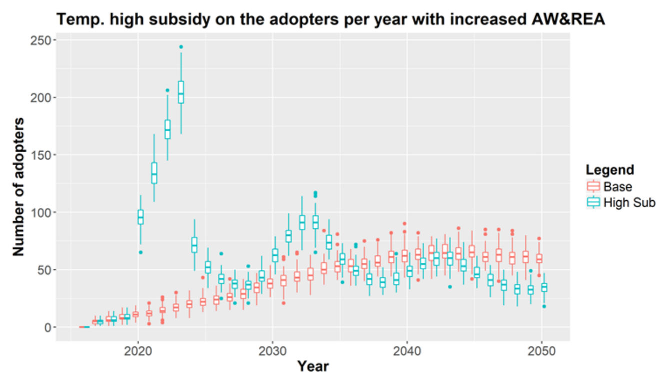


Figure 59: The adopters per year, DISC-C. AW = Awareness, REA = reason.

The results of the DISC-C experiment show an oscillation in Figure 58 and Figure 59

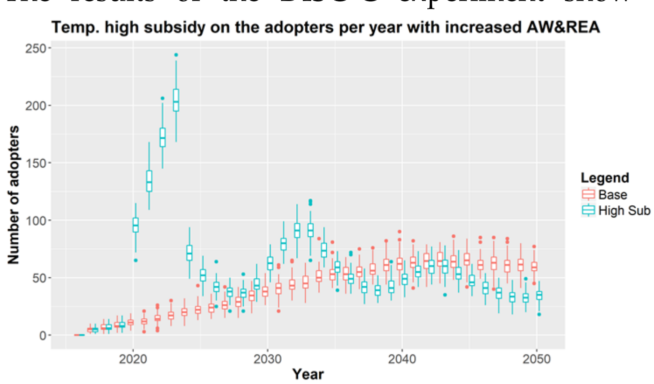


Figure 59. The origin of the oscillation is in the working of the reason. During the years of high subsidy, all households have an increased chance of having a reason. This means more households reset their reason-counter. Is also means that a large group, who have set their reason-

counter back to 0, have the same value of reason-counter. Once this groups reason-counter is approaching 10 in the next 10 years after the subsidy measure, many of them have a reason at the same time, again, resulting in a peak. The influence of the starting year, the duration and awareness increase are as can be found in C.6. The earlier the starting-year, the higher the adoption in 2050. Logically, the longer the duration, the higher the adoption. Similar argument is true for the awareness increase value. The observed pattern, as in the steep increase followed by an oscillated increase, does not change.

7.6 Conclusion

Two types of experiments were set up, one where the general behaviour of the model was analysed. The model was run for 100 years from 2017 to 2117, as in 2050, the behaviour was not stabilized yet. It can be concluded that the model follows a similar pattern to that of Rogers's diffusion of innovation theory. Subsequently, the influence of the four parameters was analysed. Based on these results, the research question *"What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using Agent Based Modelling?"* can be answered. It can be concluded that none of the parameters had a significant effect on the general pattern of adoption. Under all parameter settings, the emergent behaviour of the model was an S-shaped pattern. Of the four parameters, subsidies and the gas price growth per year have the largest influence on the adoption rate. The possibility of the leasing has little influence on the overall adoption, because it only improves the investment factor for some households, and within that factor, the influence is not crucial.

The parameter sweep was adjusted accordingly to the results of the parameters separately. As the lease or buy decision, or the energy label requirement did not have a significant influence on the results, these factors were left out of the parameter sweep. The consequence was that the parameter sweep consisted of only the gas price and the subsidy. In total, five scenarios were presented. The emergent pattern of most of the scenarios is similar to that of the base scenario. The *Customer Choice* scenario however shows an almost linear growth until 2050. A longer model run is needed to conclude if this also results in an S-shaped curve. The *Electrification* scenario shows an total adoption of heat pumps of around 85% in 2050. In this scenario, the subsidy and gas price increase are both very high. Also it is concluded that high subsidy levels (80-100%) causes higher heat pump adoption compared to high gas price growths (4-5% per year). Judging these results, the government should put more focus on higher subsidies, instead of increasing the gas prices.

A further exploration of the model was done by changing the duration of the financial incentives. Instead of fixed measure over the complete time-frame, a short spike of subsidy or gas price was set up. A short spike in subsidy or gas prices changed the emergent pattern of adoption slightly, as the adopters per year were much higher for the duration of the incentive. Another experiment was executed where a temporary high subsidy goes along with higher awareness levels and a higher chance on reason for all households. This lead to drastic changes in model behaviour. The adoption skyrockets in the years of the incentives.

8

Validation, sensitivity analysis and model use

8.1 Validation

The validation concerns the question whether model was build right and fits the intended purpose (K. H. van Dam et al., 2013). Four possible ways of validation are possible, according to (K. H. van Dam et al., 2013): (1) Historic replay, (2) Face validation through expert consultation, (3) Literature validation and (4) Model replication. As the model aims to gain insight in heat pump diffusion in future decades, historic replay is not possible. Innovation diffusion predictions can only be validated ex post, which make validation difficult, or as Kiesling et al. (2011, p39) put it: "Due to the inherent problem that innovation diffusion predictions can only be validated ex-post, all of them are, at least to some extent, speculative thought experiments until data for validation becomes available". Validation therefore is more aimed at seeing if it is fit for purpose (É. Chappin, 2011, p150). Model replication is outside of the scope of this research, which leaves expert validation and literature validation. The former is especially useful to see whether the model is fit for purpose.

8.1.1 Expert validation

Expert validation was conducted at Alliander with Arjan Bakkeren, who is an expert on the subject of customer behaviour and diffusion of technology. Arjan was enthusiastic about the model. The assumption made for the model were acceptable, with the notation that these should be extensively tested. Two other remarks were made which could improve the model. One is a measure which is called *Building-related financing*[11] owned houses, which is aimed at making all existing owned houses CO_2 neutral. With this measure, the residents do not own the new installations (such as a heat pump) any longer, but instead they rent is from a party that owns the

[11] Gebouwgebonden financiering in Dutch

installation, which could be an energy supplier, a municipality or construction company (Schootstra, 2015). This measure shifts the burden of making a house CO_2 neutral to other parties than households, thereby lowering adoption barriers. Another addition could be the development of heat grids. For instance, one could set up that 20% of households will shift to heat grids, thereby being unable to adopt a heat pump (or with a much lower chance).

8.1.2 Literature validation

Validation using scientific literature is not possible, as the most similar studies have shorter time frames and have different scopes (Snape et al., 2015; Sopha et al., 2013). Comparison with innovation diffusion literature, such as Rogers's diffusion of innovation (Rogers, 1983), is shown in 2.2.1. It was concluded there that the overall behaviour of the model is similar to that of Rogers's theory. This does not necessarily make it fit for purpose. In reality, disruptions can cause sudden changes in adoption. Such disruptions are not included in the model, which is why it follows a an S-curve quite clearly. Disruptions can be in the shape of government policy. A subsidy budget for instance, could greatly influence the adoption rate, as is shown by the significant influence of the subsidy budget in 7.3.5.

Comparing the model and its results with scientific literature is thus limited. What is possible, is to take a look at the reports presented in the market potential overview in 1.2.3. The first comparison is made with the adoption curves made at Alliander as input for the ANDES model. This was done based on the equation by Fisher and Pry (see 2.2.1), and is shown in Figure 60. The model's behaviour shows a pattern which is largely similar to one of a mathematical equation, that is purposefully fitted towards an S-shaped curve (Fisher, 1971). The reason for this is not only the absence of disruptions which was mentioned prior, but also because of the limited autonomy in the model. This will be further elaborated in the discussion in 9.2. Other prominent market reports on the subject, provide results concerning the geographical spread per municipality and don't show the overall adoption curve (CE Delft, 2015) or show general adoption numbers at a certain year.

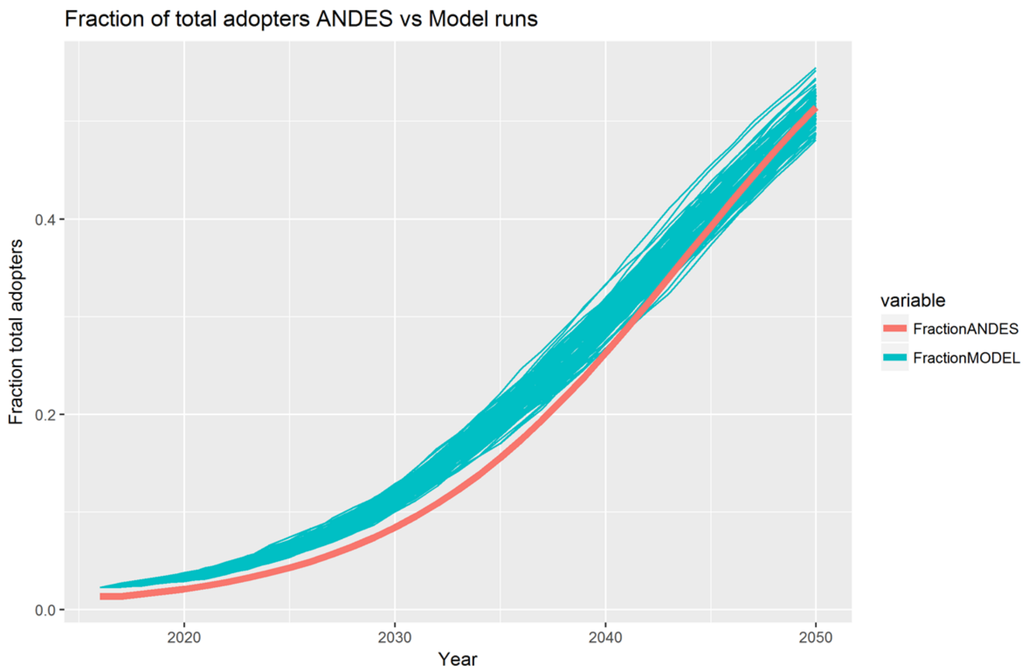


Figure 60: Comparison of Fischer and Pry and model runs. With ANDES is meant the input for the ANDES Model, which thus is Fisher and Pry.

8.2 Sensitivity analysis

A short sensitivity analysis was conducted on multiple variables. The Boolean variables were either switched on or off. All integer variables had their base value and -10 and +10 percent. The variables and their values were set according to

Table 25: Variables and their settings of the sensitivity analysis

Variable	Lower bound	Main	Upper bound
Percent Subsidized	0,225	0,25	0,275
Gas Price Growth	0,018	0,02	0,022
Electricity price growth	0,018	0,02	0,022
Emission factor growth	0,018	0,02	0,022
Experience value	0,198	0,22	0,242
Network costs growth	0,018	0,02	0,022
Initial gas price	0,63	0,7	0,77
Initial electricity price	0,1449	0,161	0,1771
Initial emission factor	0,3195	0,355	0,3905
Initial network costs	180	200	220
Reason	On	N.A.	Off
Awareness	On	N.A.	Off

Resources	On	N.A.	Off

The results can found in Appendix D:. The sensitivity of the percent subsidized, gas price growth, initial network costs, the emission factor, the experience parameter, network costs growth and initial CO2 per kWh is low. The initial gas price and initial electricity price showed more sensitivity. The starting value thus show more sensitivity than the growth rates. This is of course due to these growth rates. A higher starting point will relatively lead to higher prices because of the exponential growth. The model is especially sensitive to the conditional checks of the model: the resource check, reason and awareness. The reason and awareness put filters on the households that participate in the decision making, thus the sensitivity of these elements is also not surprising.

8.3 How can and should the model be used

At Liander, the adoption curves are not the final output. It functions as an input for the ANDES model, which analyses the amount of assets (transformers etc.) that may be overloaded at some point in time based on the curves. ANDES covers all households however, and the model in this thesis does not include rental houses, thus an adoption curve needs to be used for this type of houses. The model is the first piece in a puzzle, see Figure 61. Under the assumptions made, the model thus gives similar results. It must be noted that the results of the ANDES curves includes both rentals and owned houses. Would the adoption of rental houses follow the same pattern, the model results can be used. If adoption in rental houses is distinctive from owned houses, this should be analysed first.

Because the adoption rate of the fitter Fisher and Pry curve and the HP model are similar, then which model should be used? The added value of the ABM model lies in the fact that it can be easily extended, and that multiple initial settings can be altered. Would for instance become clear that the government increases the subsidy for a number of years, or the exact opposite? Then the height of the subsidy can be altered. Gas prices are suddenly expected to increase? The gas price can be altered. Similar arguments can be made for the electricity price, emission key figures or the COP of heat pumps. With the Fisher and Pry model, such changes cannot be tested. Adding to this is the use of the model for policy makers. They could explore the effect of different policy choices in the model, where the results could give insight in policy design. The policies currently included, subsidy and energy-label requirement might be worked out in more detail for the model be become of real use for policy makers. The energy-label requirement could be specified further in for instance a financial incentive such as a fine, or tax advantages. Subsidy could be more detailed by implementing subsidy budgets, which are time dependent, or dependent on the adoption rate at a certain time.

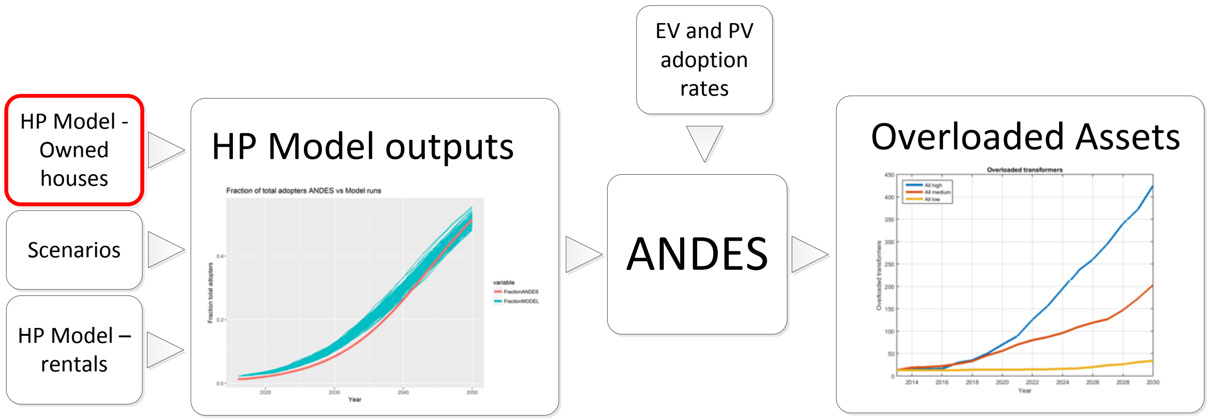


Figure 61: The position of the model in the process of analysing the geographical spread in the Liander Region. The Overload Assets graph on the right is taken from van Westering et al., (2016). It shows how many assets are overloaded under different scenarios (low, middle, high)

Furthermore, the ABM model of heat pumps is not the only model aimed to be made as inputs for ANDES. Similarly, EV and PV adoption is assumed to have a big impact on Liander's assets. Some elements of the HP model could be used for the diffusion of EV and PV. This includes the syntax of the model, but also the types of decision factors.

Another group of interest for this model are other researchers who would like to explore different scenarios for heat pump diffusion. The model thereby contributes to understanding the workings of heat pump diffusion. Lastly, the model also provides information on the diffusion per heat pump type. This could give installers insight in how they may develop heat pumps. In Chapter 7 it is concluded that hybrid heat pumps and ASHPs are adopted way more than GSHPs. As hybrid heat pumps partly consist of a ASHP unit, it might be useful for installers and heat pumps producers to put attention to developing improved ASHP instead of GSHPs.

8.4 Conclusion

Validating an ABM is difficult, especially when it concerns an innovation diffusion study that can only be really validated ex-post. Validation checks that were possible are expert validation and literature validation. The model shows very similar behaviour to that of Fisher and Pry, which is the mathematical model underlying the curves that are used for the ANDES model at Liander. The model is sensitive to the conditional checks (reason, awareness and resource check) as well as the initial gas and electricity prices. The other tested variables showed low sensitivity when increased or decreased with 10%.

Furthermore, the model should be seen as a first exploration of heat pump diffusion in the Netherlands. Based on the model, researchers, DSOs and policy makers could explore different scenarios, and possibly extend some parts of the model to their liking. Furthermore, the installers could use the model to gain insight in the popular heat pump types of the future.

Part IV

Chapter 9: Conclusion & Discussion

Chapter 11: Reflection and lessons learned

9

Conclusion and discussion

This chapter handles the conclusion (9.1) as well as the discussion (9.2). The research question is answered and in the discussion the results are reflected, limitations are discussed and future research is provided.

9.1 Conclusion

The research presented in this thesis was aimed at the exploration of different financial incentives that might influence the diffusion of heat pumps in the region of DSO Liander in the Netherlands. The currently installed dominant gas boilers are expected to be replaced by a different heating system under the current CO_2 reduction goals of the Dutch Government. This following research question was formulated to give insight in these developments:

> ***What is the influence of financial incentives on the diffusion of heat pumps in the Netherlands using Agent Based Modelling?***

To answer this question, a psychological decision making model called the Theory of Planned Behavior (TPB) was combined with innovation diffusion literature to construct an agent based model (ABM). Multiple scenarios with different financial incentives were modelled to explore the effectiveness of the incentives separately as well as combined. The answer to the research question is set up by answering the sub questions one by one. Note that the conclusion is within the model scope, assumption and limitations in this thesis, which can be found in 73Chapter 6: and paragraph 9.2.

1: What is a suitable diffusion theory to function as a basis of the model?

Innovation diffusion literature provides many different theories, which can be divided in mathematical theories and psychological theories. Purely mathematical equivalents were found to lack the heterogeneity and micro-level factors that are so important for innovation diffusion. Psychological models are therefore a more suitable fit for modelling heat pump diffusion. Of these psychological models, the Theory of Planned Behaviour (TPB) is found to be a proper model to effectively capture all relevant factors. The TPB assumes that humans have certain intentions for a behaviour, which is influenced by an Attitude (what consequences result from this behaviour?), Social Norms (morals, what does my environment think?) and a Perceived Behavioural Control (am I convinced that I can indeed perform this behaviour?).

2: What factors are identified in the literature to influence diffusion of HPs and should therefore be included in the model?

A total of eight main factors were selected based on a literature review: (1) Savings: the total savings over the life time of a heat pump, (2) Energy-label stimulation: stems from a hypothetical situation where the government puts pressure on households to improve their energy-label, (3) Social influence: represents the adoption rate in the social network of a household, (4) Investment costs: concerns the total upfront investment for a heat pump system, (5) Payback time, (6) Income, (7) Environmental benefit: a factor that represents the amount of reduced CO_2 emissions when a heat pump is adopted compared to the old situation with a gas boiler and (8) Hassle factor: the inconvenience the implementation of a heat pump brings. Besides these factors, it was also identified what policy measures would be possible. The government can stimulate heat pump adoption through multiple financial incentives such as subsidies, energy prices, VAT on heat pumps and through regulatory measures such as increasing the insulation requirements (EPC or BENG). Leasing or lending and learning effects can also have an effect and were included in the model.

3: How do the factors of question 2 fit within the diffusion theory of question 1 to form an ABM and how should the overall ABM look like?

The eight decision factors were integrated in the TPB. The social influence and energy label stimulation form the social norm, investment costs and income determine the perceived behavioural control and the hassle, payback time, environmental benefit and savings add up to the attitude. Before a household evaluates all decision factors in the model, first it has to go through a number of conditional checks. It needs a reason to adopt, and needs to be aware of the existence of heat pumps. If the households does not have the required resources, which are a suitable house type and investment budget, adoption is not possible.

4: What insight can be gained from the results of the experiments of financial incentives?

Four parameters were selected for exploration of the financial incentives. These were the energy-label stimulation, lease or buy decision, gas price growth per year and the percent subsidized.

The general behaviour under fixed parameters of the model is similar to that of Rogers's diffusion of innovation, meaning that household adopt according to an S-shaped pattern in the model. None of the financial incentives, apart or combined, lead to a significant change in this S-shaped pattern, thus the emergent pattern stays the same. Of the four incentives, subsidies and the gas price growth per year have the largest influence on the adoption rate. A high subsidy also resulted in relatively more ASHP and GSHP, whereas a high gas price resulted in increased adoption for all HP types.

The possibility of leasing has minor influence on the overall adoption, because it only improves the investment factor for some households, and within that factor, the influence is not crucial. A leasing construction including LTH and insulation was also tested, and resulted in much higher adoption rate.

Five scenarios were modelled based on the gas price growth and subsidy level. The highest adoption rates take place when both the subsidy is high and the gas price growth is high, which is not a surprising result. Also, subsidizing almost the complete investment of a heat pump system results in a higher adoption than a gas price growth of 4 to 5% per year. This implicates that the government may consider to increase the subsidy levels, in order to reach CO_2 neutral residential heating.

Of the income groups, the highest and lowest income showed little sensitivity to either higher gas prices or higher subsidy. The effect was biggest on the mid incomes. The lowest income group has a simply to low budget for any investment, while the highest income group can afford a heat pump, not matter the costs.

Further experiments were executed with the subsidy and gas price by in introducing a temporary incentive. For a short period of time the subsidy or gas price was increased instead of the whole time period. The model shortly moved away from the S-curve as the adopters per year were a lot higher during the period of the incentive. For both subsidy and gas the total adopters increased during the incentive, yet for gas this was not true for the total adopters in 2050. The reason was the fact that the gas price was set back to the original price before the measure. So would such a measure be implemented, than the gas price should be adjusted to the economic growth. For a higher subsidy, the total adopters per year increased and the adoption remained high after the temporary measure. The experiment with the largest influence is when the subsidy affects the awareness and reason. This increases the adopters per year enormously. The patter of the adoption is also no longer according to an S-curve. After the spike of adopters during the high subsidy, the adopters per year is oscillating over time. This is due to the working of the reason of the households.

The influence of financial incentives on the diffusion of heat pumps in the Netherlands

The influence of the financial incentives can be split in two. There is the energy label requirement and leasing which have relatively little effect and on the other side the gas price growth and subsidy, greatly altering the adoption of heat pumps. The economic aspects, payback time, savings and the investment costs are the reason for these differences. This economic barrier proves also to be the determining factor in this thesis. Leasing constructions for just the heat pumps will not help much according to this model. Only when the total investment is lowered by leasing, thus also LTH and insulation, leasing will be an effective tool for stimulating heat pump adoption. A high gas price growth, surprisingly also stimulates hybrid heat pump adoption just as much as AHPS and GSHP, even though the HHPs still use gas. The little amount of gas still being used is thus of much influence on the total variable costs.

When looking at specific groups and their adoption behaviour, then the middle incomes are most affected by subsidies and leasing (that is leasing for the HP, insulation and LTH). As for the household groups, generally the groups with the lowest average incomes, the unaware energy users and faithful environmentalist, are most affected.

The best option for heat pump adoption might be to look into raising awareness of households. An experiment where the subsidy affected the awareness and reason of households, shows a drastic increase in adoption. It must be noted that the relation between subsidy vs awareness and reason was not implemented based on extensive research, but rather to explore the effect.

9.2 Discussion of results, limitations and future research

The discussion consists of three parts. In 9.2.1 it will be discussed how the results should be interpreted and how they meet certain expectations. These expectations are either based on literature or on common sense. The limitations or the research are described in 9.2.2 and the recommendations for future research in 9.2.3.

9.2.1 Interpretation of the results

The S-Shaped pattern of the model

The general behaviour of the model shows that the adoption process follows an S-shaped curve rather perfectly. Although such diffusion S-curves are generally assumed to accurately describe an innovation diffusion process, this does not mean that such curves are fully in line with reality. Such behaviour is also not highly surprising and is easily explainable. Firstly, there are no elements in the model that could cause large diffusion discontinuities in the behaviour. Secondly, due to feedback effects present in the learning rate, heat pump costs decrease and the COP improves. This in turn improves the savings (better COP), investment costs (lower HP costs), environmental benefit (higher COP) and payback time (better savings and investment costs). Another feedback effect is present in the social influence when the total adopters increase (more adopters in the social networks). Thus, more than half of the factors, 5 out of 8, are increasing when the total adoption increases. Thirdly, none of the factors in the model can decrease, thus either the factors remain the same in a year, or they improve. Of course these factors are also dependent on the characteristics of the model, but except for the energy-label, parameters such as the yearly gas usage and income are considered rather static. The more adopters per year, the higher the learning effects, the higher the adopter per year and so on, until a certain maximum number of adopters is reached, and the slope declines.

Adoption per heat pump type

The adoption per heat pump type is in line with expectations. As GSHPs generally have the highest cost, and largest hassle, they are not preferred by many households. That hybrids (which are in essence ASHPs with a backup) are popular, is specifically because of these aspects. Insulation measures and low temperature heating (LTH) is not a necessity, which greatly lowers the costs and lowers the hassle. It is a logical result that hybrid heat pumps are most adopted.

The ABM model versus the mathematical Fisher and Pry model

The results show that the results of the models experiment is an S-curve, similar to Rogers DoI. Also, from the validation followed that the model results follow a similar pattern as Fisher and Pry model which is used at Alliander, which are based on a mathematical equation and empirical market research. In chapter 2, it was argued that mathematical approaches are not ideal for innovation diffusion studies, as they generally lack the possibility for communication between agents, lack heterogeneity, do not take into account micro-level factors of adoption and cannot accurately describe how households with different preferences make decisions. In the model these aspects are taken into account, yet the results are similar. This might indicate that the decision making process is modelled rather simple and households make rather rational decisions. The variance of the results also indicates that the model is fairly deterministic. Also the interaction between the agents in the model is minimal. The social influence does involve some interaction, however, this factor has a limited effect on the model results.

The question thus arises whether this model is of added value compared to Fisher and Pry and the Bass model. Shouldn't a mathematical model be used instead of this ABM if the results are similar? For the main version of the model, the answer is yes. The four incentives in this model could be altered and set for the entire period results in diffusion curves that are likely to be reproduced by mathematical models such as Fisher and Pry or the Bass model. However, when the financial incentives become dynamic over time (shown in 7.5), the model provides an edge over the mathematical models. This effect was visible for a temporary high subsidy and gas price for 1 to 5 years, as well as for a static and adaptive subsidy budget. The real added value of the model is provided by the experiments where the awareness and reason are altered (7.5.3). Here the model shows behaviour which is not possible with conventional mathematical models, or at least under the basic conditions of the Bass model described in Chapter 2. This does not imply that these results are realistic however, as the oscillation in the model is probably not a realistic consequence of such a measure. It must also be noted that the implementation of the dynamic incentives is suitable for more research, as the implementation was done rather quickly.

Effect of the financial incentives

The results of the effect of the parameters (financial incentives) on the behaviour are thus not disruptive, but rather straightforward. More subsidy or a higher gas price leads to more adoption. It is difficult to assess what has a bigger effect on the diffusion, a high subsidy or a high gas price, as the parameters represent something entirely different. The parameters that have a lower effect, are the lease or buy decision and the energy label requirement. That leasing does not have a very strong effect, makes sense as the total upfront costs of heat pump system is not solely dependent on the heat pump, but also on the needed insulation and low temperature heating. The latter are almost always needed in the residential existing houses in scope. Leasing thus only has an effect when the heat pump costs make up the majority of the total upfront costs.

9.2.2 Limitations of the research

The difficulty of using 8 decisions and the level of influence per factor

The model comprises a total of 8 decision factors, which all weigh equally. The consequence is that all factors only provide a small share in the total intention. Since the payback time, savings and the investment cost are all implemented separately, and the payback time directly follows from the savings and investment cost, an improvement in one of these two also improves the payback time. The economic aspects therefore have a stronger presence than the other factors. One could argue that only the payback time should be included. However, the perceived behavioural control of TPB represents the perceived ease or difficulty of performing the behaviour (Ajzen, 1991). It was reasoned that the investment costs fits this description rather well, thus the investment cost was included separately. At the same time however, this would lead to inequalities between the heat pump types. A HHP is cheap and a GSHP is expensive. Hence the savings are also included. The costs effects between the heat pumps were now equal, but the other factors were now less influential on the behaviour.

The working of the reason

In the model, the chance that a household will evaluate a heat pump is equal for all households. Most households will have a reason after 10 years. Multiple things are not included in the working of the reason. First, the reason is likely different per household. Second, the reason is likely influence by other household characteristics, such as the income or the environmental awareness. It is thus questionable if the reason should be included in the model. It functions as a major filter on the households that make a decision.

Households perception

The perception of the households is only implemented in a limited way. Based on the report on which the household groups are based (Randsdorp & Schoemaker, 2014) weights were assigned to what was assumed to be the set of most important factors for a group. It was not possible to derive weights for all the factors. The report did not supply the needed information for that purpose.

The lease-or-buy decision

The lease or buy decision has been implemented in such a way that the upfront costs decrease for households. The formalization of this decision however, is simplistic and does not include all elements of a leasing contract. Only the reduced upfront costs are taken into account, thus only the positive effects are included. Realistically, leasing would lead to a higher total investment costs over the lifetime of a heat pumps due to interest rates. The payback time thus would decrease. Furthermore, different lease options are possible which influences the economic risk.

With operational lease, the risk is at the leasing company, while financial lease puts the risk at the household. Many more aspects of leasing are left out, mostly the psychological aspect of leasing. For instance the endowment effect, which simply put, means that people prefer to own stuff and value things higher merely because they own them (Kahneman, Knetsch, & Thaler, 1990). The lease or buy construction should thus be viewed as an approximate representation of a real lease or buy decision.

The maximum investment budget for a household

Based on the household's income, each household is assigned a certain budget, which limits the maximum investment they can afford. In the model, if the investment costs are higher than this budget, a household will not be able to buy the heat pump (the resources check in 6.4.4). Although the assumption that a higher income leads to higher investment budgets, this is not always true. A household consisting of a family with children has less room for investment than a couple without children with the same income. The spendable income would be a better suitable parameter. However, this was not available in the EDM dataset, and known spendable incomes could not be related to the income classification of EDM. Therefore assumptions needed to be made about the budget.

Energy-label improvements and the energy-label requirement

In the model, the energy label increases each year for certain number of households, irrespective of their characteristics. This is unrealistic, as such energy label upgrades require investments, which not all households will or can do. The energy label requirement is also not independent of the perception of households on this label. Now the factor is highest when the energy label is lowest. However, it could be that a household perceives the stimulation higher with an energy label of 3 compared to a household that has an energy label of 7.

Geographical aspects

Geographical aspects are absent in the model. As mentioned in 6.7, the soil type is not included, as well as space available. In reality, terraced houses with no or small garden, barely have the possibility to install a GSHP. Also not all households live on ideal soil types for GSHP, so although GSHP adoption is already lower than ASHP and HHP, in reality this might even turn out lower.

Apartments and heat pump adoption

In the dataset, households living in apartments are included, as it was assumed that they could install a hybrid heat pump or a full on air sourced heat pump. The calculation of the insulation costs for apartment owners is very likely resulting into high costs. Their floors and roofs do not need the insulation levels of the normal ground level house types (detached, terraced etc.). Also apartment complexes are mostly part of an organization that takes care of the complex as whole, including insulation measures. It is also not certain if all apartment complexes are suitable even for ASHP and hybrid heat pumps. The structure should be strong enough to hold ASHP installations, there should be enough space available as well. It is more likely that apartment complexes will have heat provided by either deep geothermal wells, residual heat from industry or biogas provided by a central unit (block heating). Maybe big heat pump installations are possible, but this then will be big installations place on the roof. These solutions would be out of the scope of this research, as that has to be decided by organizations (such as housing corporations), rather than individual households in this situation. Maybe some smaller heat pumps are possible in a hybrid solution individually.

The hassle factor

Based on Snape et al. (2015) the hassle factor was static for the complete model run, and was the same for each household. This is because there is not much known about the influence of the hassle on heat pump diffusion. In reality, the hassle will be perceived differently per household. Also, due to increasing experience by the installers and possible innovations in the technology, it might be possible that installation of a heat pump results in less inconvenience over time.

9.2.3 Recommendations for future studies

The awareness thus is one of the most important factors of the model. In the model, the awareness of households could only be activated by peers, media and via installers. Through feedback effects more households become aware, as installers experience improves and more peers have a heat pump. Originally, there was no connection however, between the financial incentives and the awareness. In the experiments where this connection was added, the results were promising. It is an interesting subject that could be analysed. It is not unthinkable that a high subsidies for instance are paired with a promotional campaign by governmental organisations, thus raising awareness. Especially as deadlines for climate policy goals come closer. Similarly to the awareness, the reason also greatly influences the amount of adopters per year. Further research into the moment when people consider a new heating system would be valuable, as well as how this could be influenced.

Aside from the awareness and reason, it could be interesting to just look into more adaptive financial incentives for heat pumps. In this situation, a government could be modelled as an agent, making autonomous decisions based on the adoption rates given by the model. Let this government chance the subsidy and gas prices or other measures. It must be said that modelling governments behaviour is easier said than done, with the capricious nature of governments and policies.

In this thesis, the preferences and important factors are mostly based on assumptions. Similar arguments are true for the weights. It is not known what the opinion of Dutch households is on heat pumps at the moment. Therefore an empirical study on opinions of households could lead to interesting insights, and possibly a better basis for a diffusion model. The difficulty of modelling human behaviour however, does not change.

One actor in the system in Chapter 4 are the installers. The role of this actor is rather limited, while they could have a high influence on households. A model could be made where the installers are given certain behaviour, reacting to market developments and government policies. They could 'visit' households in the model and give them advice. This gives a better understanding in the role of the installers in an adoption process.

The model in this thesis only covers the owned houses, whereas a large share of the households do rent houses, which also have to find an alternative for gas. A next step would be to make a model where the adoption in rental houses is analysed. This implicates modelling at least two types of agents: the households and the housing corporations. Housing corporations invest on a much bigger scale and have different decision mechanisms than households.

In the model, only heat pump technology is a possible option, next to gas boiler. Giving households the possibility to choose between multiple options, such as in Sopha et al. (2013) could possibly give better insight in households choices. Heating systems such as heat grids, biogas or pellet heaters could be added. For this model, the geographical location should be included, as heat grids are dependent on residual or geothermal heat.

Including the geographical location can lead to interesting results. This could be combined with including other technologies such as geothermal and residual heat. This almost directly implicates to model governmental organizations as agents next to heat retailers and heat network operators. Municipalities are probably also important here. Another idea is to model municipalities as agents, and instead of individual households, one could model entire neighbourhoods as agents.

A model could also be made with more focus on the adoption of insulation and low temperature heating. A household could also calculate an intention for insulation and LTH, and adopt these technologies, irrespective whether a heat pump will be adopted. This would give a better representation to the adoption of hybrid heat pumps than in the model of this thesis, where the household does not adopt better insulation measures or other low temperature heating separately from heat pumps. In reality however, households are still advised to use LTH when a hybrid heat pump is preferred. LTH is mostly a consequence of the heating system. Insulation however, is something that can lower the energy bill of household on itself. That is why a model where adoption of insulation and heat pumps separately could lead to interesting results.

10

Reflection

10.1.1 Evaluation of application of the TPB

Modelling consumer or households behaviour with all the soft factors is a challenging task. This was known in advance (see 2.1.2). In the search of some guidance, the TPB was found to be the most suitable theory on which the decision process should be based. In the first stages of determining the decision process, it was tried to structure the decision process based on the TPB. The model as of now, could be set up without mentioning the TPB at all. The decision factors could be added and the same intention would follow. This means the TPB more functioned as a guidance what factors to include. Literature using the TPB were diverse in the implementation of the theory, indicating that there is no commonly accepted method in applying the TPB in an ABM.

The TPB thus did not structure the decision process as intended in the first period of this research. It is still advised however for other researchers with similar subjects to use the theory, as it does give good insights concerning what beliefs humans generally have. This gives structure to the thought process when deciding upon the decision factors in the model. It cannot be concluded based on this thesis whether the TPB is indeed better to use than the Consumat approach (Janssen et al., 1999) or the CADM (Klöckner & Blöbaum, 2010).

10.1.2 Reflection on the agent-based model

In 2.1.2, the disadvantages of ABM according to Bonabeau (2002) were shown. During the process of making the model, it can be said that all three of these were encountered.

"Human behaviour comprises soft factors (irrational behaviour, subjective choices etc.), can be very difficult to capture, although ABM is the only modelling language to deal with such situations"

In the previous paragraph, something was already said about the difficulty of modelling human behaviour. Aside from using the TPB, the soft factors were difficult to implement. In hindsight, the formalization of the decision factors only made the households more rational as time progressed. Due to the difficulty of modelling the soft factors, the focus was set to first to realize the formalization of the factors that were clear, such as the costs elements. At some point, the general thought process was to formalize all processes rather rationally. Relatively late in the research, this was pointed out by someone at Alliander[12]. This is when two adjustments were made in the model to include some more autonomy in the decision of households. One at the reason (6.2.1.13) and the other at the adoption decision between the heat pump types (6.4.5). After these adjustments, the autonomy in the model was still not strongly present, which can be seen in the rather predictive behaviour of the model. Subjective choices were present with some weights, but this was not based on empirical data, but on assumptions. The difficulty to capture the soft factors thus resulted in almost no soft factors in the model.

"The model has to be built at the right level of description, with just the right amount of detail to serve its purpose; this remains an art more than a science"

Generally, the amount of detail per decision factor is not properly balanced. The costs, payback time, savings and environmental benefit are worked out relatively detailed, while the other four factors, social influence, income, energy label stimulation and the hassle are implement quite simply. Working a factor out in more detail does not make it necessarily better, but some more attention towards these factors could have led to a more accurate description of the factors.

"Modelling at a very low level makes simulation of all the different agents' very computation intensive and time-consuming"

Although the model runs are not long at all, running experiments of a parameter space of 4 parameters quickly leads to many model runs, that could easily run for days when using 100 repetitions. Especially after more output variables were generated and I had to run multiple experiments on my own laptop instead of an external server, this issue became apparent.

[12] Thanks to M. Danes

10.1.3 Personal reflection

Making decisions

The main lesson learned in the process concerns making definitive decisions. The process of going from the system to a final model felt endless. Between the first version of the decision processes around five months passed. At some point, the modelling in Netlogo started, but his process was still in an iterative process. This is not ideal, as the complete process should be worked out before the model is constructed. The lesson here is first to fully analyse how a part in the model should work and then implement it.

Start with analysing the outcome of the model early in the process and watch out for tunnel vision

Another lesson learned is to make some graphs and conclusions earlier in the process. This gives a better idea of the direction of the research, even though the model could be far from finished. Running Netlogo from R with the RNetlogo package[13] is a useful method to quickly run some experiments. A valuable lesson learned in relation to this is the relevance of the sensitivity analysis. This was performed more or less within the model, however, this was not complete, ill performed and documented. At a later stage in the process it was discovered that awareness and reason lead to drastic changes in the model results. In hindsight, this is logical of course. I had tunnel vision on the previously proposed financial incentives. This resulted in two measures having barely having any influence (lease and BENG-regulation) and a missed opportunity to test incentives aimed at raising awareness. Such choices are always difficult of course. As such incentives in turn would require quite some extra desk research into the workings and implementation. I think the solution is to have an idea concerning the input parameters for the experiments, but to be flexible if it turns out other factors are more interesting.

Tunnel vision

Some practical lessons are to log the changes that are made each new model version, and to document verification right away. During this research, more than once a verification step was executed, while this was tested and verified during some point earlier in the process. Proper version management, logging changes in the model and verification documentation are things that definitely would have been used would similar research be performed another time. Similar argument are with performing the experiments. At some point, many experiments where conducted, with multiple model versions. The overview was sometimes lost. Constructing the output in R also provided valuable lessons. I found myself more and more learning how to construct many plots in a short time. Then again, next time I would think harder on what I want

[13] https://cran.r-project.org/web/packages/RNetLogo/index.html

to plot. Not just the content, but also the axis, the size, the names. Doing it properly once saves a lot of time and frustration.

References

Ajzen, I. (1991). The Theory of Planned Behavior. *Organizational Behavior and Human Decision Processes*, *50*, 179–211. Retrieved from http://ac.els-cdn.com/074959789190020T/1-s2.0-074959789190020T-main.pdf?_tid=4792152c-0efc-11e7-b359-00000aacb361&acdnat=1490186415_ad709e8d52cf7028f288807d6757dbfb

Alliander. (2015). *Jaarverslag 2015. Zonder energie staat alles stil*.

Balcombe, P., Rigby, D., & Azapagic, A. (2013). Motivations and barriers associated with adopting microgeneration energy technologies in the UK. *Renewable and Sustainable Energy Reviews*, *22*, 655–666. https://doi.org/10.1016/j.rser.2013.02.012

Barabási, A.-L., & Albert, R. (1999). Emergence of Scaling in Random Networks. *Science*, *286*(5439). Retrieved from http://science.sciencemag.org/content/286/5439/509.full

Bass, F. M. (1969). A New Product Growth for Model Consumer Durables. *Management Science*, *15*(5), 215–227. https://doi.org/10.1287/mnsc.15.5.215

Bewustnieuwbouw.nl. (2016). EPC, Energielabel A en nul-op-de-meter - Bewust Nieuwbouw. Retrieved May 27, 2017, from https://www.bewustnieuwbouw.nl/epc-energielabel-en-nul-op-de-meter/

Bjørnstad, E. (2012). Diffusion of renewable heating technologies in households. Experiences from the Norwegian Household Subsidy Programme. *Energy Policy*, *48*, 148–158. https://doi.org/10.1016/j.enpol.2012.04.078

Blum, P., Campillo, G., & Kölbel, T. (2011). Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany. *Energy*, *36*(5), 3002–3011. https://doi.org/10.1016/j.energy.2011.02.044

Bonabeau, E. (2002). Agent-based modelling: methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, *99 Suppl 3*(suppl 3), 7280–7. https://doi.org/10.1073/pnas.082080899

BOSCH. (n.d.). *Programma EnviLine II*.

Brown, M., & Stebnicki, J. (2011). *Air Source Heat Pump Efficiency Gains from Low Ambient Temperature Operation Using Supplemental Electric Heating*. Retrieved from http://www.franklinenergy.com/wp-content/uploads/2014/10/AirSource-Heat-Pump-Efficiency-Gains-2011.pdf

Burley, J., & Pan, W. (2010). ADOPTION OF AIR SOURCE HEAT PUMPS FOR LOW CARBON

HOMES, 6–8. Retrieved from http://www.arcom.ac.uk/-docs/proceedings/ar2010-1361-1370_Burley_and_Pan.pdf

CBS. (2011). Inkomen hoogopgeleiden bijna het dubbele van dat van laagopgeleiden. Retrieved September 11, 2017, from https://www.cbs.nl/nl-nl/nieuws/2011/12/inkomen-hoogopgeleiden-bijna-het-dubbele-van-dat-van-laagopgeleiden

CBS. (2017a). Aardgas en elektriciteit, gemiddelde prijzen van eindverbruikers. Retrieved March 19, 2017, from http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=81309NED&D1=0-1,3,5,7-8,11,15&D2=0&D3=a&D4=a&HD=121114-1344&HDR=G1,G2,T&STB=G3

CBS. (2017b). CBS StatLine - Bevolking en bevolkingsontwikkeling; per maand, kwartaal en jaar. Retrieved August 27, 2017, from http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=37943ned&D1=383-388&D2=203,220,237,254,271,288,305,322,339,356,373&HDR=T&STB=G1&VW=T

CBS. (2017c). CBS StatLine - Warmtepompen; aantallen, thermisch vermogen en energiestromen. Retrieved January 17, 2017, from http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=82380NED&LA=NL

CBS. (2017d). Warmtepompen; aantallen, thermisch vermogen en energiestromen. Retrieved March 17, 2017, from http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82380ned&D1=0-2,6&D2=0-2&D3=a&D4=19-21&VW=T

CE Delft. (2015). *Op weg naar een klimaatneutrale gebouwde omgeving 2050*.

Chappin, E. J. L. (2011). *Simulating Energy Transitions*. *PhD Thesis*. https://doi.org/ISBN: 978-90-79787-30-2

Chappin, E. J. L., & Afman, M. R. (2013). An agent-based model of transitions in consumer lighting: Policy impacts from the E.U. phase-out of incandescents. *Environmental Innovation and Societal Transitions*, *7*, 16–36. https://doi.org/10.1016/j.eist.2012.11.005

Chappin, E. J. L., & Dijkema, G. P. J. (2010). Agent-based modelling of energy infrastructure transitions. *Int. J. Critical Infrastructures*, *6*(2), 106–130. Retrieved from http://www.inderscienceonline.com/doi/pdf/10.1504/IJCIS.2010.03107

Chua, K. J., Chou, S. K., & Yang, W. M. (2010). Advances in heat pump systems: A review. *Applied Energy*, *87*(12), 3611–3624. https://doi.org/10.1016/j.apenergy.2010.06.014

CLO. (2015). Isolatiemaatregelen woningen, 1982-2012 | Compendium voor de Leefomgeving. Retrieved August 4, 2017, from http://www.clo.nl/indicatoren/nl0383-isolatiemaatregelen-woningen

Dam, K. H. van, Nikolic, I., & Lukszo, Z. (2013). *Complex adaptive Systems. Agent-Based Modelling of Socia-Technical Systems*. https://doi.org/10.1007/978-94-007-4933-7

Dam, M. van. (2016). The added value of Agent Based Modelling in modelling electricity distribution networks .

DELTA. (2012). *2050 Pathways for Domestic Heat*. Retrieved from http://www.energynetworks.org/assets/files/gas/futures/Delta-ee_ENA Final Report OCT.pdf.pdf

Dieperink, C., Brand, I., & Vermeulen, W. (2004). Diffusion of energy-saving innovations in industry and the built environment: Dutch studies as inputs for a more integrated analytical framework. *Energy Policy*, *32*(6), 773–784. https://doi.org/10.1016/S0301-4215(02)00341-5

Dutch Heat Pump Association. (2013). *Positioning paper "Warmtepompen en economie."* Retrieved from http://www.dhpa-online.nl/wp-content/uploads/2013/09/Warmtepompen.economie.pdf

ECN. (2016a). *Energietrends 2016*. Retrieved from https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-O--16-031

ECN. (2016b). *Nationale Energieverkenning 2016*. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2016-nationale-energieverkenning-2016_2070.PDF

Fisher, J. C. (1971). A Simple Substitution Model of Technological Change*. *The Biology of Population Growth*, 75–88. Retrieved from http://ac.els-cdn.com/S0040162571800057/1-s2.0-S0040162571800057-main.pdf?_tid=29733222-0eea-11e7-b2d3-00000aab0f02&acdnat=1490178633_789275a2e293b9a579f88bb041d838c1

Florides, G., & Kalogirou, S. (2007). Ground heat exchangers-A review of systems, models and applications. *Renewable Energy*, *32*(15), 2461–2478. https://doi.org/10.1016/j.renene.2006.12.014

Friege, J., Holtz, G., & Chappin, E. J. L. (2016). Exploring homeowners' insulation activity. *Journal of Artificial Societies and Social Simulation*, *19*(1), 1–20. https://doi.org/10.18564/jasss.2941

Graziano, M., & Gillingham, K. (2014). Spatial Patterns of Solar Photovoltaic System Adoption : The Influence of Neighbors and the Built Environment ǂ, 1–44.

Heiskanen, E., & Matschoss, K. (2016). Understanding the uneven diffusion of building-scale renewable energy systems: A review of household, local and country level factors in diverse European countries. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2016.11.027

Hlavinka, A. N., Mjelde, J. W., Dharmasena, S., & Holland, C. (2016). Forecasting the adoption of residential ductless heat pumps. *Energy Economics*, *54*, 60–67. https://doi.org/10.1016/j.eneco.2015.11.020

Houwing, M., & Bouwmans, I. (2006). AGENT-BASED MODELLING OF RESIDENTIAL ENERGY GENERATION WITH MICRO-CHP. Retrieved from http://www.nextgenerationinfrastructures.eu/catalog/file/430788/Paper_Houwing_2.pdf

ISSO. (2005). Ontwerp van individuele en kleine elektrische warmtepompsystemen. Retrieved August 7, 2017, from https://kennisbank.isso.nl/docs/publicatie/72/2014

Janssen, M. A., Vlek, C. A. J., & Jager, W. (1999). *Consumats in a commons dilemma: Testing the behavioral rules of simulated consumers*. Groningen.

Jensen, T. (2017). *Simulating co-diffusion of innovations: Feedback technology & Behavorial change*. Delft University of Technology.

Kahneman, D., Knetsch, J. L., & Thaler, R. H. (1990). Experimental Tests of the Endowment Effect and the Coase Theorem. *Journal of Political Economy*, *98*(6). Retrieved from http://www.journals.uchicago.edu/doi/pdfplus/10.1086/261737

Karytsas, S., & Theodoropoulou, H. (2014). Public awareness and willingness to adopt ground source heat pumps for domestic heating and cooling. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2014.02.008

Kiesling, E., Günther, M., Stummer, C., & Wakolbinger, L. M. (2011). Agent-based simulation of innovation diffusion: a review. *Central European Journal of Operations Research*, *20*(2), 183–230. Retrieved from https://pdfs.semanticscholar.org/3662/7db9636d938dca2647c4fa8a7b76d511a8d2.pdf

Klöckner, C. A., & Blöbaum, A. (2010). A comprehensive action determination model: Toward a broader understanding of ecological behaviour using the example of travel mode choice. *Journal of Environmental Psychology*, *30*, 574–586. https://doi.org/10.1016/j.jenvp.2010.03.001

Krogt, R. Van Der. (2011). *Energie uit de ondergrond: potenties en kartering*.

Leenheer, J., De Nooij, M., & Sheikh, O. (2011). Own power: Motives of having electricity without the energy company. *Energy Policy*, *39*, 5621–5629. https://doi.org/10.1016/j.enpol.2011.04.037

Lin, M., & Li, N. (2010). Scale-free network provides an optimal pattern for knowledge transfer. *Physica A: Statistical Mechanics and Its Applications*, *389*(3), 473–480. https://doi.org/10.1016/j.physa.2009.10.004

Macal, C., & North, M. (2014). Introductory tutorial: Agent-Based Modelling and Simulation. In *Proceedings of the 2014 Winter Simulation Conference* (pp. 2239–2250).

Mahajan, V., Muller, E., & Bass, F. M. (1995). Diffusion of New Products: Empirical Generalizations and Managerial Uses. *Marketing Science*, *14*(3_supplement), G79–G88. https://doi.org/10.1287/mksc.14.3.G79

Mahapatra, K., & Gustavsson, L. (2008). An adopter-centric approach to analyze the diffusion patterns of innovative residential heating systems in Sweden. *Energy Policy*, *36*(2), 577–590. https://doi.org/10.1016/j.enpol.2007.10.006

Meijer, G. (2017). De toekomst: met een duurzame warmtepomp de winter door. *Volkskrant*. Retrieved from http://www.volkskrant.nl/economie/de-toekomst-met-een-duurzame-warmtepomp-de-winter-door~a4493541/

Michelsen, C. C., & Madlener, R. (2016). Switching from fossil fuel to renewables in residential heating systems: An empirical study of homeowners' decisions in Germany. *Energy Policy*, *89*, 95–105. https://doi.org/10.1016/j.enpol.2015.11.018

Ministry of Economic Affairs. (2016a). *Energieagenda Naar een CO_2-arme energievoorziening*.

Ministry of Economic Affairs. Vaststelling begroting Ministerie van Economische Zaken en Diergezondheidsfonds 2017 (2016). Retrieved from http://www.rijksbegroting.nl/2017/voorbereiding/begroting,kst225626_36.html

Ministry of Economic Affairs. Wijziging van de Wet opslag duurzame energie in verband met de vaststelling van tarieven voor 2017 (2016). Retrieved from http://www.energiemarktinformatie.nl/downloads/nota-naar-aanleiding-van-verslag-over-wijziging-wet-opslag-duurzame-energie.pdf

Moglia, M., Cook, S., & McGregor, J. (2017). A review of Agent-Based Modelling of technology diffusion with special reference to residential energy efficiency. *Sustainable Cities and Society*, *31*, 173–182. https://doi.org/10.1016/j.scs.2017.03.006

Motivaction. (n.d.). Het Mentality-model. Retrieved May 22, 2017, from https://www.motivaction.nl/mentality/het-mentality-model

Mustafa Omer, A. (2008). Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews*, *12*(2), 344–371. https://doi.org/10.1016/j.rser.2006.10.003

Negro, S. O., Alkemade, F., & Hekkert, M. P. (2012). Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renewable and Sustainable Energy Reviews*, *16*(6), 3836–3846. https://doi.org/10.1016/j.rser.2012.03.043

Noonan, D. S., Chiang Hsieh, L.-H., Matisoff, D., Hsieh, L.-H. C., & Matisoff, D. (2013). Spatial Effects in Energy-Efficient Residential HVAC Technology Adoption. *Environment and Behavior*, *45*(4), 476–503. https://doi.org/10.1177/0013916511421664

Otten, M. B. J., & Afman, M. R. (2015). Emissiekentallen elektriciteit - Kentallen voor grijze en "niet-geoormerkte stroom" inclusief upstream-emissies, 1–8.

Palmer, J., Sorda, G., & Madlener, R. (2015). Modelling the diffusion of residential photovoltaic systems in Italy: An agent-based simulation. *Technological Forecasting & Social Change*, *99*, 106–131. https://doi.org/10.1016/j.techfore.2015.06.011

PBL. (2014). *Op weg naar een klimaatneutrale woningvoorraad in 2050*. The Hague. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2014-op-weg-naar-een-klimaatneutrale-woningvoorraad-in-2050_738.pdf

PBL. (2017). *Toekomstbeeld Klimaatneutrale warmtenetten in Nederland*. The Hague. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2017-toekomstbeeld-klimaatneutrale-warmtenetten-in-nederland-1926.pdf

Rai, V., & Robinson, S. A. (2015). Agent-based modelling of energy technology adoption: Empirical integration of social, behavioral, economic, and environmental factors. *Environmental Modelling and Software*, *70*, 163–177. https://doi.org/10.1016/j.envsoft.2015.04.014

Randsdorp, Y., & Schoemaker, R. (2014). Consumentensegmentatie Stedin, 73.

Rijksoverheid, Milieucentraal, RVO, & VNG. (2017). Energie besparen doe je nu. Retrieved August 28, 2017, from https://www.energiebesparendoejenu.nl/

Rogers, E. M. (1962). *Diffusion of Innovations* (4th ed.). Retrieved from https://books.google.nl/books?hl=nl&lr=&id=v1ii4QsB7jIC&oi=fnd&pg=PR15&dq=diffusion+of+innovation+rogers&ots=DK_xsKYqcR&sig=eCiY6cStrsjP4sBc9QumS857tHA#v=onepage&q=diffusion of innovation rogers&f=false

Rogers, E. M. (1983). *DIFFUSION OF INNOVATIONS Third Edition Library of Congress Cataloging in Publication Data THE AMERICAN CENTER LIBRARY* (Third). New York: Macmillan Publishing Co. Retrieved from https://teddykw2.files.wordpress.com/2012/07/everett-m-rogers-diffusion-of-innovations.pdf

Rooijers, F., Schepers, B., & Cherif, S. (2015). Verschuivingen energiebelasting, 1–15.

RVO. (2016). Investeringssubsidie duurzame energie (ISDE). Retrieved November 17, 2016, from http://www.rvo.nl/subsidies-regelingen/investeringssubsidie-duurzame-energie

Sarbu, I., & Sebarchievici, C. (2014). General review of ground-source heat pump systems for heating and cooling of buildings. *Energy and Buildings*, *70*, 441–454. https://doi.org/10.1016/j.enbuild.2013.11.068

Scholten, D., Künneke, R., Heldeweg, M., Van Bueren, E., Butenko, A., Hoppe, T., … Rosen, M.

A. (2016). Towards the Comprehensive Design of Energy Infrastructures. *European Consortium for Political Research*, 1–29. https://doi.org/10.3390/su8121291

Schootstra, S. (2015). Gebouwgebonden financiering versnelt verduurzaming woningen - EnergieOverheid. Retrieved October 19, 2017, from http://www.energieoverheid.nl/2015/11/06/gebouwgebonden-financiering-versnelt-verduurzaming-woningen/

Schreinemachers, P., Berger, T., Sirijinda, A., & Praneetvatakul, S. (2009). The Diffusion of Greenhouse Agriculture in Northern Thailand: Combining Econometrics and Agent-Based Modelling. *Canadian Journal of Agricultural Economics/Revue Canadienne D'agroeconomie*, *57*(4), 513–536. https://doi.org/10.1111/j.1744-7976.2009.01168.x

Schwarz, N., & Ernst, A. (2009). Agent-based modelling of the diffusion of environmental innovations — An empirical approach. *Technological Forecasting and Social Change*, *76*(4), 497–511. https://doi.org/10.1016/j.techfore.2008.03.024

Snape, J. R., Boait, P. J., & Rylatt, R. M. (2015). *Will domestic consumers take up the renewable heat incentive? An analysis of the barriers to heat pump adoption using agent-based modelling*. *Energy Policy* (Vol. 85). https://doi.org/10.1016/j.enpol.2015.05.008

Sopha, B. M., & Klöckner, C. A. (2011). Psychological factors in the diffusion of sustainable technology: A study of Norwegian households' adoption of wood pellet heating. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2011.03.027

Sopha, B. M., Klöckner, C. A., & Hertwich, E. G. (2010). The Influence of the Social Network Structure on the Diffusion of Heating System in Norway. In *World Congress on Social Simulation*. Tapei. Retrieved from https://repository.ugm.ac.id/32780/1/10_Sem_WCSS_2010.pdf

Sopha, B. M., Klöckner, C. A., & Hertwich, E. G. (2013). Adoption and diffusion of heating systems in Norway: Coupling agent-based modelling with empirical research. *Environmental Innovation and Societal Transitions*. https://doi.org/10.1016/j.eist.2013.06.001

Van der Veen, R. A. C., & Kasmire, J. (2015). Combined heat and power in Dutch greenhouses: A case study of technology diffusion. *Energy Policy*. https://doi.org/10.1016/j.enpol.2015.08.040

van Westering, W., Zondervan, A., Bakkeren, A., Mijnhardt, F., & van der Els, J. (2016). Assessing and mitigating the impact of the energy demand in 2030 on the dutch regional power distribution grid. *2016 IEEE 13th International Conference on Networking, Sensing, and Control (ICNSC)*, (May), 1–6. https://doi.org/10.1109/ICNSC.2016.7478981

van Zoest, P., Veldman, E., Lukszo, Z., & Herder, P. M. (2014). Analysis of future electricity demand and supply in the low voltage distribution grid. In *Proceedings of the 11th IEEE*

International Conference on Networking, Sensing and Control (pp. 619–624). IEEE. https://doi.org/10.1109/ICNSC.2014.6819697

Vasiljevska, J., Douw, J., Mengolini, A., & Nikolic, I. (2017). An Agent-Based Model of Electricity Consumer: Smart Metering Policy Implications in Europe. *Journal of Artificial Societies and Social Simulation*, *20*(1). https://doi.org/10.18564/jasss.3150

Vergeer, R. (2017). *Wie profiteert van het klimaatbeleid?* Retrieved from http://content1a.omroep.nl/urishieldv2/l27m0d7ed7292c5d2b3e0058f61557000000.cb0e58a6c95438de80af10bdd9cb8ecd/nos/docs/CE_Delft_7L42_Wie profiteert van het klimaatbeleid_def.pdf

Veselka, T., Boyd, G., Conzelmann, G., & Koritarov, V. (2001). Simulating The Behavior Of Electricity Markets With An Agent-Based Methodology : The Electric Market Complex Adaptive Systems (Emcas) Model. *United States Association for Energy Economics USAEE Conference*, (October 2015), 1–9.

Waldorp, M. (1992). *Complexity: the emerging science at the edge of order and chaos*. New York: Simon and Schuster.

Warmtepompinfo.nl. (n.d.). Kosten warmtepomp 2017 - overzicht. Retrieved March 17, 2017, from https://www.warmtepomp-info.nl/kosten-warmtepomp/

Weiss, M., Junginger, M., & Patel, M. K. (2008). *Learning energy efficiency - Experience curves for household appliances and space heating , cooling , and lighting technologies*.

Zhang, T., Gensler, S., & Garcia, R. (2011). A Study of the Diffusion of Alternative Fuel Vehicles: An Agent-Based Modelling Approach*. *Journal of Product Innovation Management*, *28*(2), 152–168. https://doi.org/10.1111/j.1540-5885.2011.00789.x

Zhang, T., & Nuttall, W. J. (2011). Evaluating Government's Policies on Promoting Smart Metering Diffusion in Retail Electricity Markets via Agent-Based Simulation. *Journal of Product Innovation Management*, *28*, 169–186. https://doi.org/10.1111/j.1540-5885.2011.00790.x

Zhao, J., Mazhari, E., Celik, N., & Son, Y.-J. (2011). Hybrid agent-based simulation for policy evaluation of solar power generation systems. *Simulation Modelling Practice and Theory*, *19*, 2189–2205. https://doi.org/10.1016/j.simpat.2011.07.005

Appendices

Appendix A: Region of Liander in the Netherlands

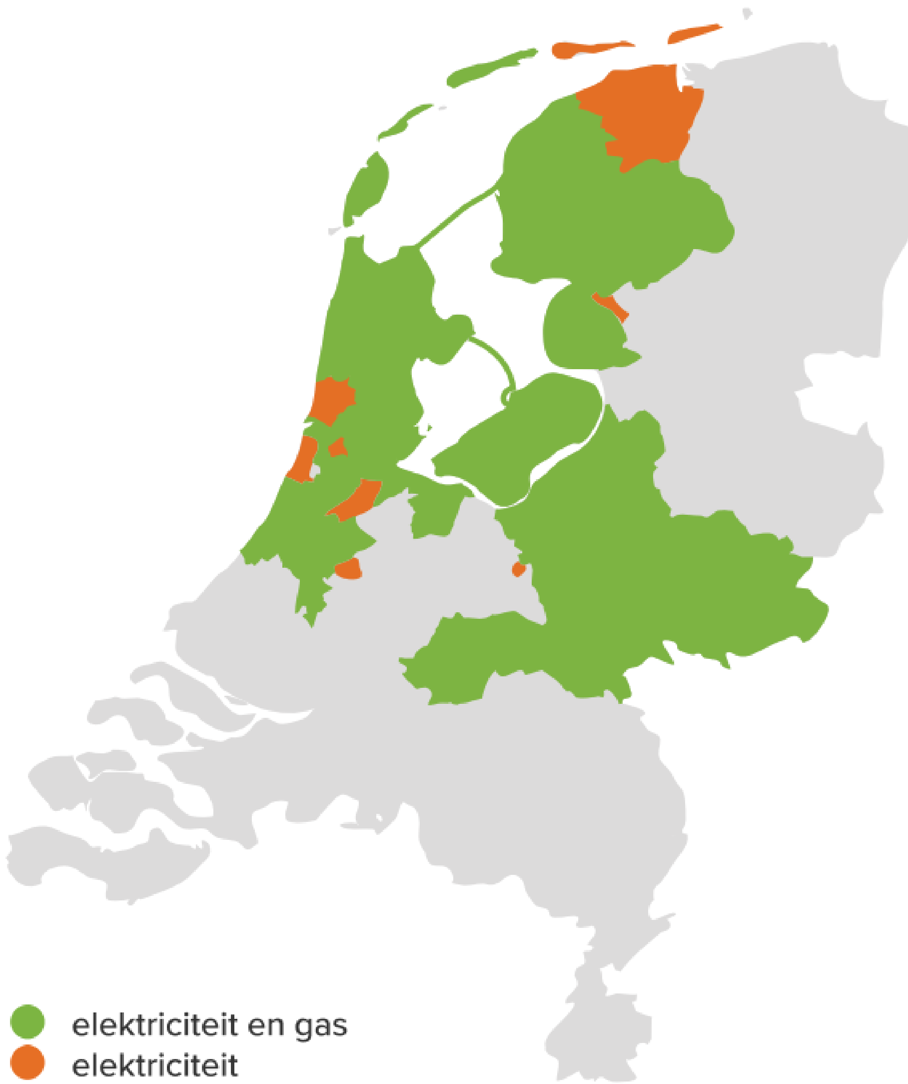


Figure 62: Region of Liander

Appendix B: Background modelling assumptions (Chapter 6)

B.1 Comparison of the data sample with the EDM dataset

The sample and the EDM dataset are compared in the tables below, this was done with average values and the standard deviation.

Household group				
	Values	EDM	Sample	Diff
HH groups share of total	1	25,40%	24,70%	0,70%
	2	23,40%	23,30%	0,10%
	3	41,70%	42,70%	1,00%
	4	9,60%	9,30%	0,30%
	Average	2,354	2,367	0,013
	Std Dev	0,963	0,956	0,007

Figure 63: Comparison of the statistics of the household group of the sample and EDM

Income				
	Values	EDM	Sample	Diff
Income share of total	1	1,80%	1,80%	0,00%
	2	3,70%	3,70%	0,00%
	3	21,40%	21,20%	0,20%
	4	31,90%	31,60%	0,30%
	5	22,20%	21,10%	1,10%
	6	19,10%	20,50%	1,40%
	Average	4,263	4,281	0,018
	Std Dev	1,198	1,215	0,017

Figure 64: Comparison of the statistics of the Income of the sample and EDM

Yearly Gas usage			
Values	EDM	Sample	Diff
Average	1575,1	1595,3	20,2
Std Dev	815,3	839,6	24,3

Figure 65: Comparison of the statistics of the yearly gas usage of the sample and EDM

Energy Label				
	Values	EDM	Sample	Diff
E-label share of	1	13,00%	13,07%	0,07%

total	2	16,20%	16,51%	0,31%
	3	26,30%	25,71%	0,59%
	4	19,00%	18,17%	0,83%
	5	11,60%	12,80%	1,20%
	6	7,70%	7,57%	0,13%
	7	6,10%	6,17%	0,07%
	Average	3,479	3,485	0,006
	Std Dev	1,67	1,67	0

Figure 66: Comparison of the statistics of the energy label of the sample and EDM

B.2 Average moves per Dutch citizen

Based on CBS data (CBS, 2017b) the average number of times a person in the Netherlands moves over a certain time period was calculated. The average number of moves over the last 10 years in the Netherlands was around 1.6 million. The average number of inhabitants of the Netherlands over that period is 16.7 million. This leads to an average number of moves per citizen of 10.4. Thus it is estimated that a Dutch citizen moves on average once every 10 years.

Year	Total Number of moves
2006	1678119
2007	1639180
2008	1632391
2009	1497820
2010	1462234
2011	1459027
2012	1478861
2013	1473168
2014	1563338
2015	1679632
2016	1791450

Table 26: Total number of moves per year in the Netherlands over the period 2006-2016 (CBS, 2017b)

B.3 Calculation of average insulation increase of houses

The number insulation measures per household increased steadily in the last decades. In order to include this development in the model, the total increase over the period 1986 to 2012 was calculated and divided by the number of years, to get the average increase per year, which can be found in the last column of Table 27.

Table 27: Insulation measures in houses in the Netherlands over the period 1986-2012 (CLO, 2015)

	1986	1990	1995	2000	2006	2012	Total increase %	per year
	% houses							
Double layered glass	38,93	49	57	69	82	86	47	1,81
Roof insulation	39,26	47	51	63	76	79	40	1,53
Wall insulation	25,02	31	41	50	55	70	45	1,73
Floor insulation	9,43	15	24	34	43	56	47	1,79
Average	28	36	43	54	64	73	45	**1,72**

B.4 Estimating the insulation costs

Based on government website www.energiebesparendoejenu.nl (Rijksoverheid, Milieucentraal, RVO, & VNG, 2017) the following costs per insulation and house type were retrieved. Would a household implement all insulation measures, the total costs would be around €13.000 per household. The insulation costs are based on the E-label. It is assumed that a house with the worst energy label, 7 (or G), has no insulation measures whatsoever. The assumption is made that the difference between the best and worst E-label is an indication of the insulation costs. The difference is 7 (worst) – 1 (best), which is 6. To get the costs per E-label step, the average insulation costs per house are divided by 6. This is rounded to €2.000 per E-label step.

Table 28: The average insulation costs per house type and the average

	Average insulation costs per house type				
Insulation type	Terraced	Corner-house	Semi-detached	Detached	Apartment
Facade	€ 800	€ 2.100	€ 2.100	€ 3.100	Unknown
Floor	€ 1.400	€ 1.600	€ 1.600	€ 2.800	Unknown
Roof	€ 4.000	€ 4.600	€ 4.600	€ 8.300	Unknown
Windows	€ 3.100	€ 3.500	€ 3.500	€ 4.600	Unknown
Total	€ 9.300	€ 11.800	€ 11.800	€ 18.800	Unknown
				Average insulation costs per house	**€ 12.925**

B.5 Calculation of the LTH costs

The dataset for this calculation was retrieved from http://www.jagapro.nl/downloads, it is an excel file with the name *Selectiemodule Installateurs, prijsniveau 2016-2017, versie 29-6-2017*. In this file all radiators of *Jaga* are listed. Four basic types of LT-radiators were filtered: Tempo Wand, Strada, Maxi Wand and Linea Plus wand, see Figure 67. This resulted in a list of 5218 types. Radiators have different heat release values, expressed in Watts, which is dependent on the supply-, return- and environment-temperature. These are classified according to the European standard EN442 for radiator power values. The four categories are 75/65/20 (supply/return/environment), 55/45/20, 45/35/20 and 35/30/20 all in degrees Celsius. Heat pumps generally release heat around 45 degrees Celsius, thereby putting them in the group 45/35/20. The next step was to divide the price by the number of Watts to retrieve the price per Watt, see Table 29. To see whether the median or the mean has to be used, a histogram was made (Figure 68). It is concluded that the distribution is not normal, therefore the median value was used for the model. This amounted to €0.77/m³. For an average household in the Netherlands with a yearly gas usage of 1600 m³, the output power is assume d to be 10 kW [14]. Following from Eq. (40), the LTH cost per m³ gas is 4.80. Thus the total costs for the low temperature heating is that number multiplied by the total yearly gas usage, as can be seen in Eq. (41).

$$LTHCostsPerGasUnit(m^3) = \frac{TotalWatt * LTHCostsPerGasUnit(m^3)}{Total\ gas\ units\ used\ (m^3)} \quad \text{Eq. (60)}$$

$$= \frac{10000 * 0.77}{1600} = 4.80\ Euro/m^3$$

$$CostLTH_i = GU_i * 4.80 \quad \text{Eq. (61)}$$

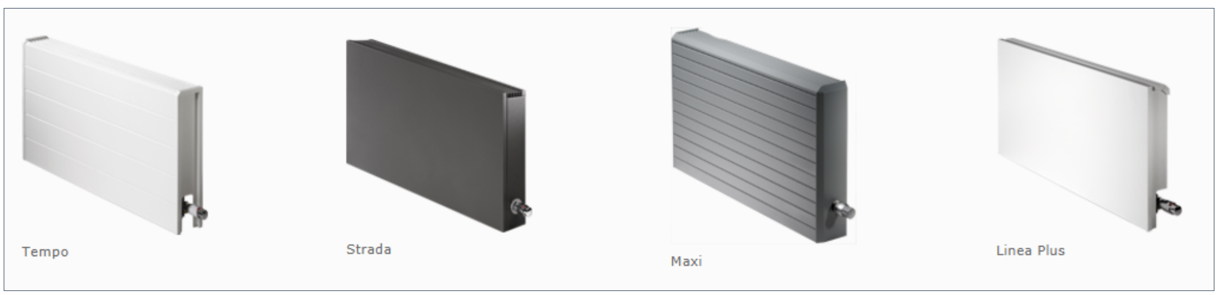


Figure 67: Images of the heat pump types

Table 29: Examples of different heat release power per supply, return and environment temperatures. This is only a short part of the complete list.

Model	45/35/20	Price	Price per Watt
Strada Wand	72	€ 128,50	€ 1,78
Strada Wand	72	€ 171,50	€ 2,38
Strada Wand	87	€ 123,30	€ 1,42
Strada Wand	87	€ 169,20	€ 1,94
Strada Wand	146	€ 153,10	€ 1,05
Strada Wand	146	€ 203,40	€ 1,39

[14] Numbers provided by Dr. T.W. Fens

…	…	…	…

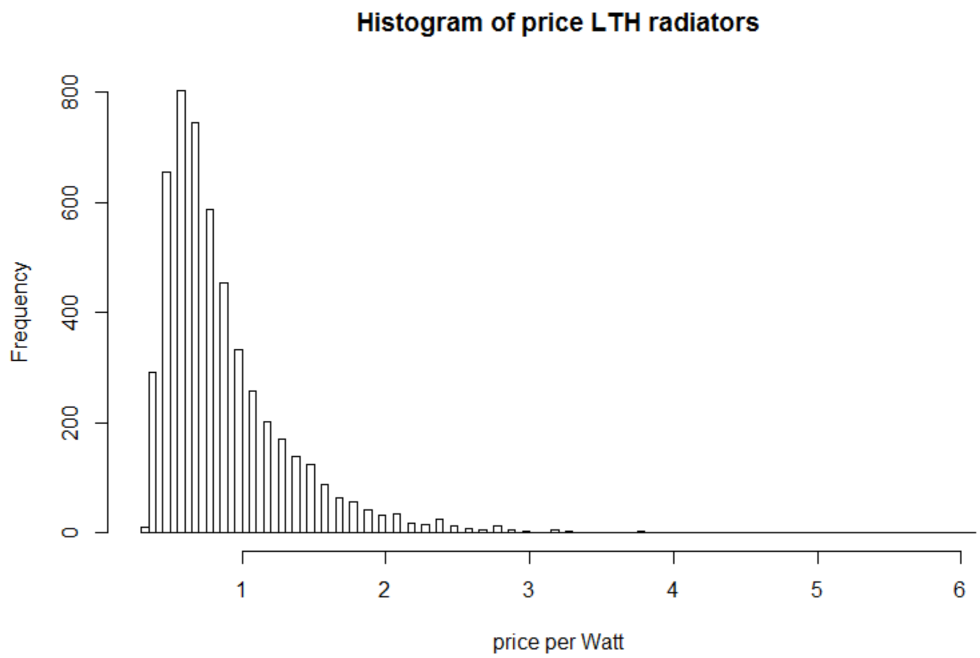


Figure 68: Histogram of the price per Watt of the different LT-Radiators

B.6 HP costs

To be able to calculate the investment costs, savings and the payback time, the heat pump costs need to be calculated. In order to do this, the ranges from multiple Dutch sources were taken. Subsequently, the average of these ranges were calculated, shown in Table 30.

Table 30: Heat pump costs of multiple Dutch sources and their averages

	HHP		ASHP		GSHP	
Source	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
warmtepomp-info.nl	5000	7000	4000	7000	10000	25000
Millieucentraal.nl	4700	6700	6500	14500	8500	16500
Warmtepomp-weetjes.nl	3600	5500	6500	14500	12000	21000
Zonnepanelen-weetjes.nl	5000	7000	10000	15000	15000	25000
Verwarmingsinfo.nl	5000	7000	4000	7000	10000	20000
Warmtepompplein.nl	4500	7000	5500	9500	15000	
eigenhuis.nl			8000	12000	10000	15000
Averages	4633	6700	6357	11357	11500	20417
In model	4500	7000	6500	11500	11500	20500
Gas-use	300	5000	300	5000	300	5000
Function	alpha	0,53	alpha	1,06	alpha	1,915
	beta	4340	beta	6181	beta	10926

By using the two points for each heat pump type, the slope *alpha* can be calculated and the constant *beta* through linear regression, leading to the following function. The beta factor is the constant that it added. This leads to equations 7, 8 and 9.

$$C_{type,t0} = GU_i \cdot alpha + beta$$

$$InitialCostHybrid_i = 0.53 \cdot GU_i + 4340 \quad \text{Eq. (62)}$$

$$InitialCostASHP_i = 1.06 \cdot GU_i + 6168 \quad \text{Eq. (63)}$$

$$InitialCostGSHP_i = 1.915 \cdot GU_i + 10926 \quad \text{Eq. (64)}$$

Where GU_i is the gas usage of a household.

B.7 The maximum intention value of households

The maximum intention value determines the speed of adoption in the model. The maximum intention was calibrated in such a way that the total fraction of adoption in 2050 amount to 50%. In Netlogo some tests runs were executed to lower the range of possible max intentions values. Then a small experiment was run were 9 maximum intention values were tested with 200 replications per maximum intention value. The average fraction of adoption was compared to the percentage of 50%, and the one with the lowest difference was chosen as maximum intention. The max intention 23.5 had the lowest difference with an adoption fraction of 50%, and is thus chosen as max intention, as can be seen in Table 31.

Table 31: Fraction of adopters in 2050 of the model and ANDES

MaxIntention	Fraction Model	Fraction calibration	Difference
22	52,879%	50,000%	0,0288
22,5	51,930%	50,000%	0,0193
23	50,626%	50,000%	0,0063
23,5	49,609%	50,000%	0,0039
24	48,751%	50,000%	0,0125
24,5	47,700%	50,000%	0,0230
25	46,835%	50,000%	0,0317
25,5	45,734%	50,000%	0,0427
26	45,056%	50,000%	0,0494

B.8 Consumer price index (CPI) developments

Table 32: Consumer price index developments from 2000 to 2017

Year	CPI	Year	CPI	Year	CPI	Year	CPI
2000	2,6	2005	1,7	2010	1,3	2015	0,6
2001	4,5	2006	1,1	2011	2,3	2016	0,3
2002	3,4	2007	1,6	2012	2,5	2017	2,76
2003	2,1	2008	2,5	2013	2,5		
2004	1,2	2009	1,2	2014	1		
Average CPI increase			**1,95**				

B.9 Network costs and vastrecht levering

The network costs and vastrecht levering are extra costs on a households energy bill. The average vastrecht levering costs are presented in Table 33, which is the average of multiple suppliers.

Then in Table 34, the Network costs are added, based on the Liander tariffs of the past 6 years. The sum of the vastrecht levering and network costs calculated, of which the average of the years is 206 euro. This is rounded down to 200 euro for the model as the initial $CostNetwork$.

Table 33: Vastrecht levering of gas of multiple suppliers in 2017. https://www.gaslicht.com/nieuws/het-vastrecht-voor-gas-en-stroom-verschilt-enorm .

Supplier	Vastrecht gas	Supplier	Vastrecht gas
NLE	22,20	Nuon	45,00
Essent	23,96	E.ON	47,88
Greenchoice	24,25	E.ON	47,92
Eneco	27,66	Energiedirect.nl	59,53
Delta	18,12	Energiedirect.nl	59,53
Electrabel	37,50	Budget Energie	71,88
Average	**40,45**		

Table 34: Network costs of Liander in the past 6 years . Source network costs: LIander. Source vastrecht levering: Table 24.

Year	Network costs	Vastrecht levering	Total
2012	166	40	**206**
2013	176	40	**216**
2014	170	40	**210**
2015	161	40	**201**
2016	148	40	**188**
2017	176	40	**216**
		Average	**206**

Appendix C: Results of the experiments

This appendix shows all results presented in Chapter 7.

C.1 Lease or buy in a standard model run

In the graphs below, the influence of the lease or buy decision is shown. In Figure 69 the adoption per heat pump type is shown, and in Figure 70 the adoption per household group. The influence of the lease or buy decision does not show large differences.

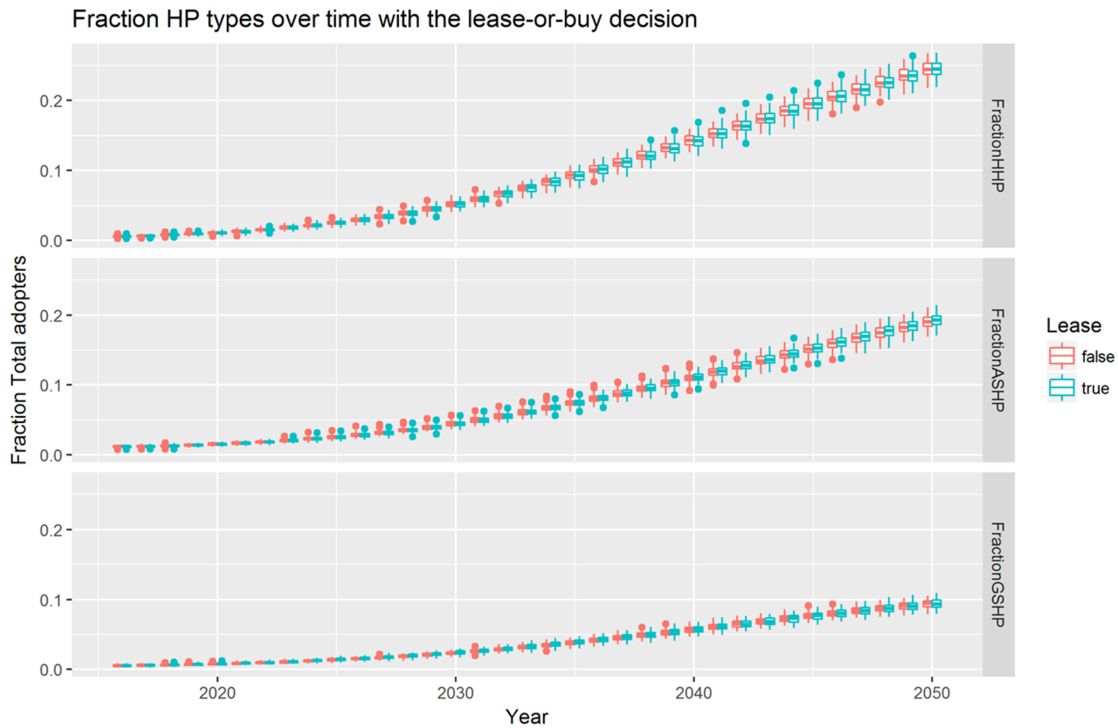


Figure 69: Adoption of heat pumps over time with the lease-or-buy decision for the three heat pump types. False means that leasing is not possible.

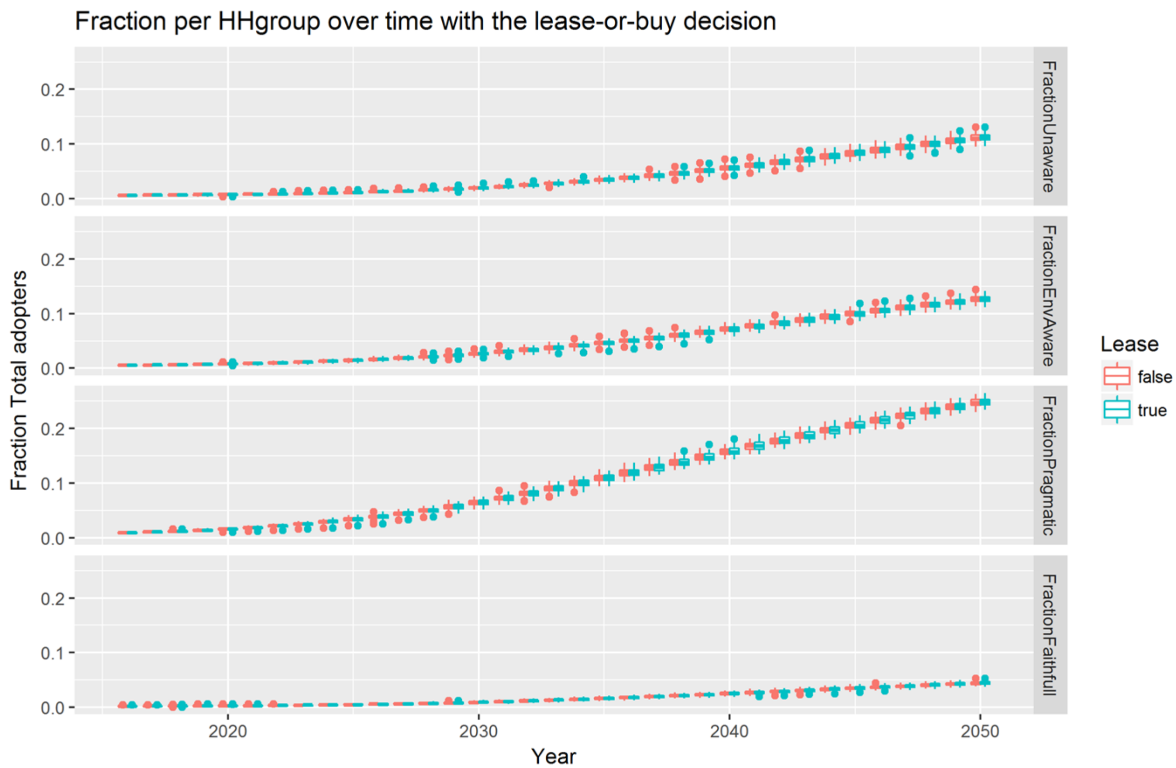


Figure 70: Adoption of heat pumps over time with the lease-or-buy decision for the household groups. False means that leasing is not possible.

C.2 Lease or buy with higher HP costs

When the heat pump cost are significantly higher, the influence of the lease or buy decision is clearly visible. The pragmatic energy users especially are adopting more when leasing is possible, see Figure 71. Considering the heat pump types, it seems that HHPs and GSHPs are more adopted, when leasing is possible, see Figure 72.

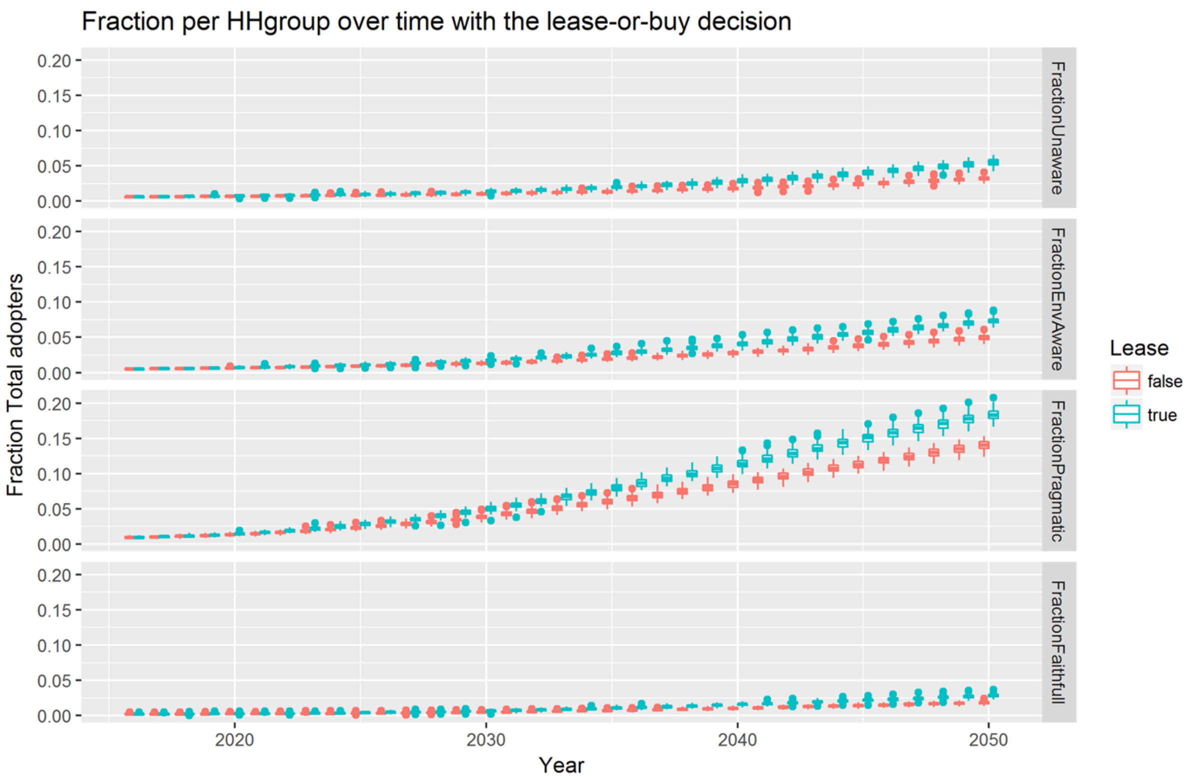


Figure 71: Total adopters for the household groups when the heat pump costs are very high

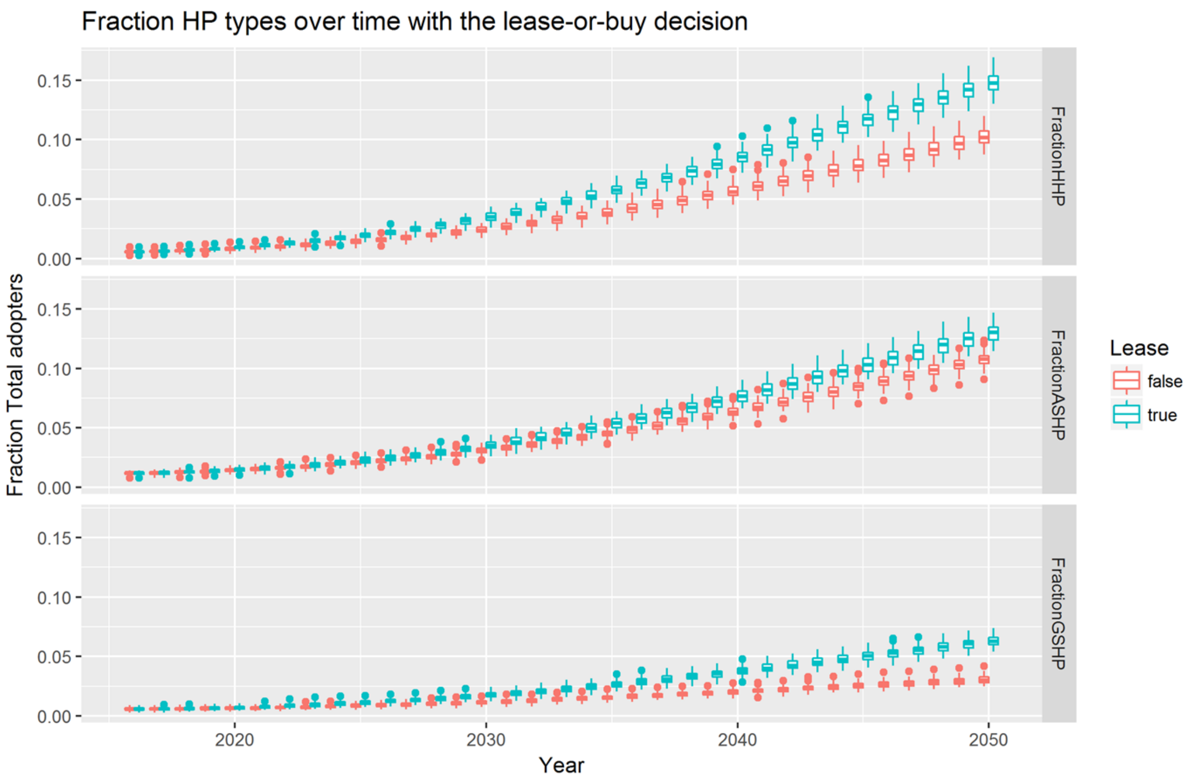


Figure 72: Adoption per heat pump type with high HP costs

C.3 Adoption of lease V2 for all heat pump types per income group

The adoption per heat pump type of the income groups is presented in Figure 73 to Figure 78. The incomes groups 2 to 4 profit most from the lease construction.

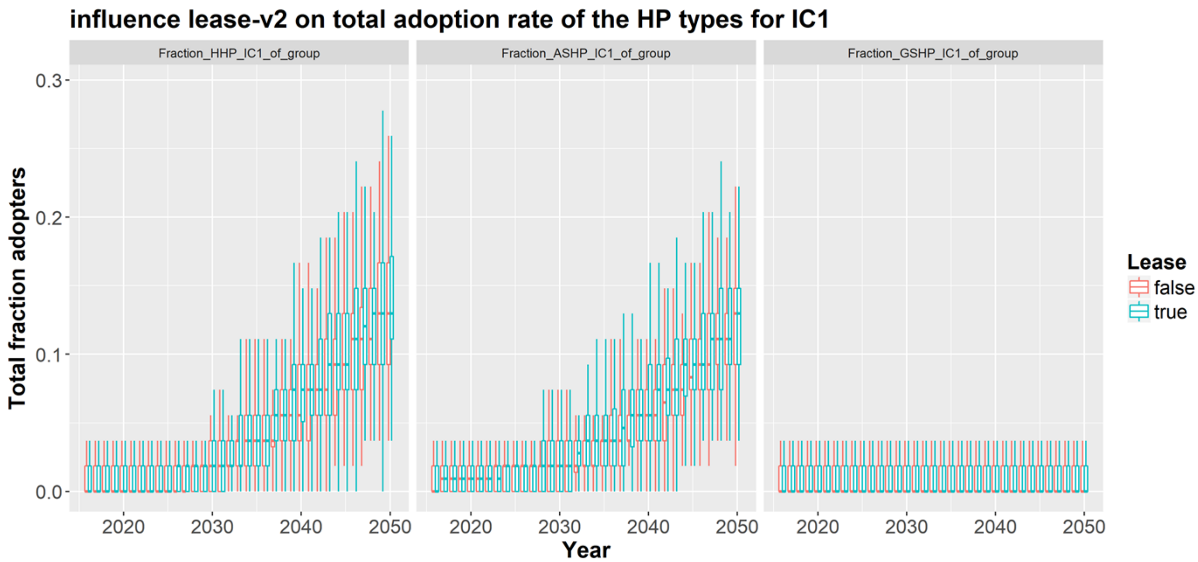


Figure 73: Adoption of the different HP types for income 1

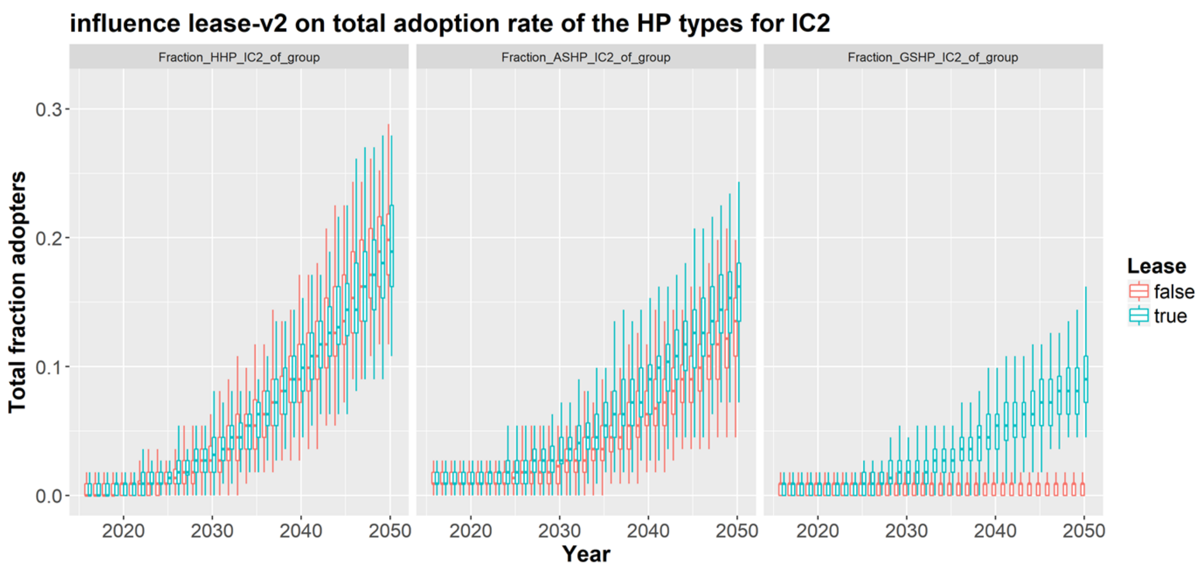


Figure 74: Adoption of the different HP types for income 2

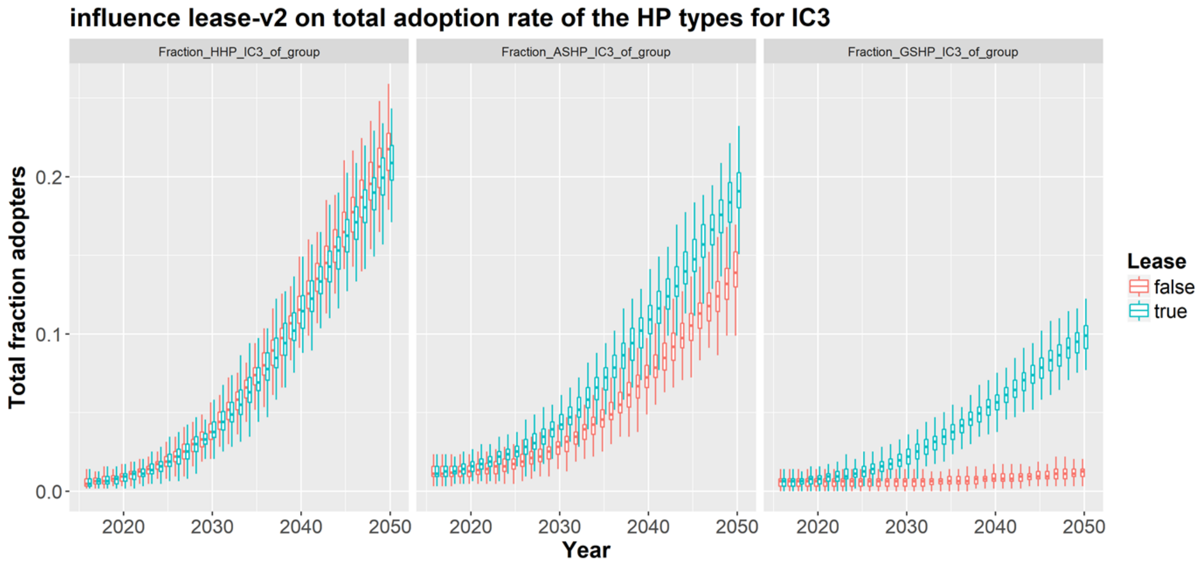


Figure 75: Adoption of the different HP types for income 3

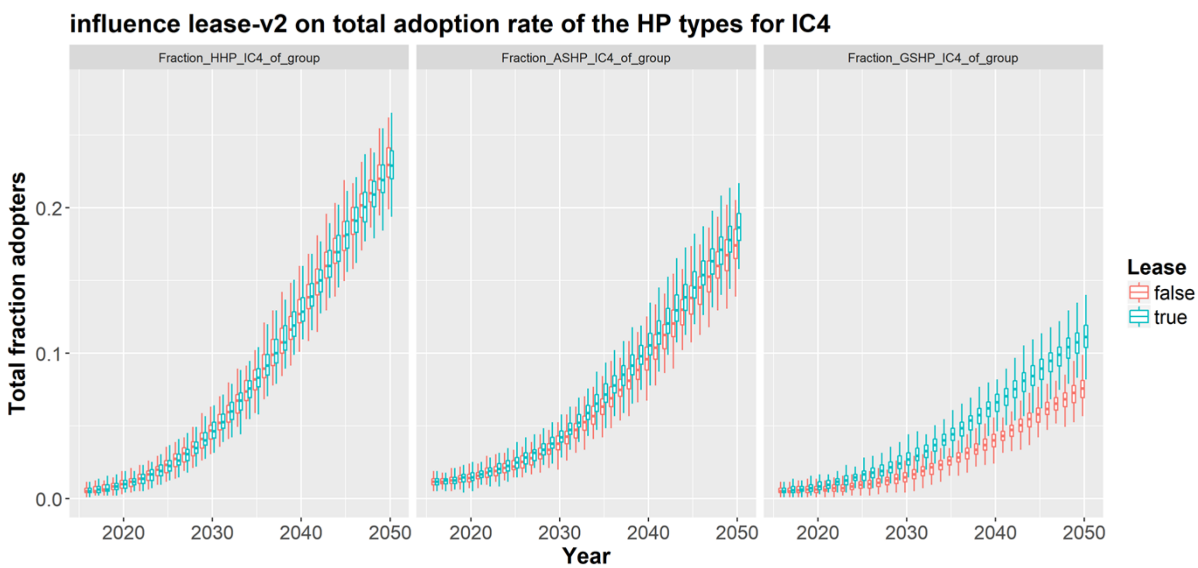


Figure 76: Adoption of the different HP types for income 4

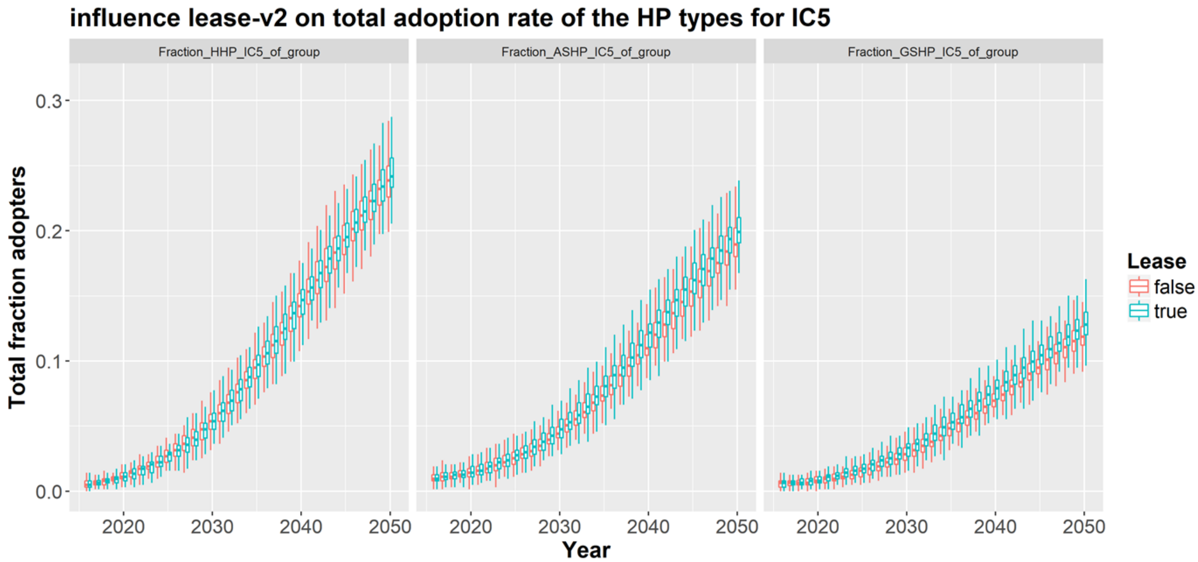


Figure 77: Adoption of the different HP types for income 5

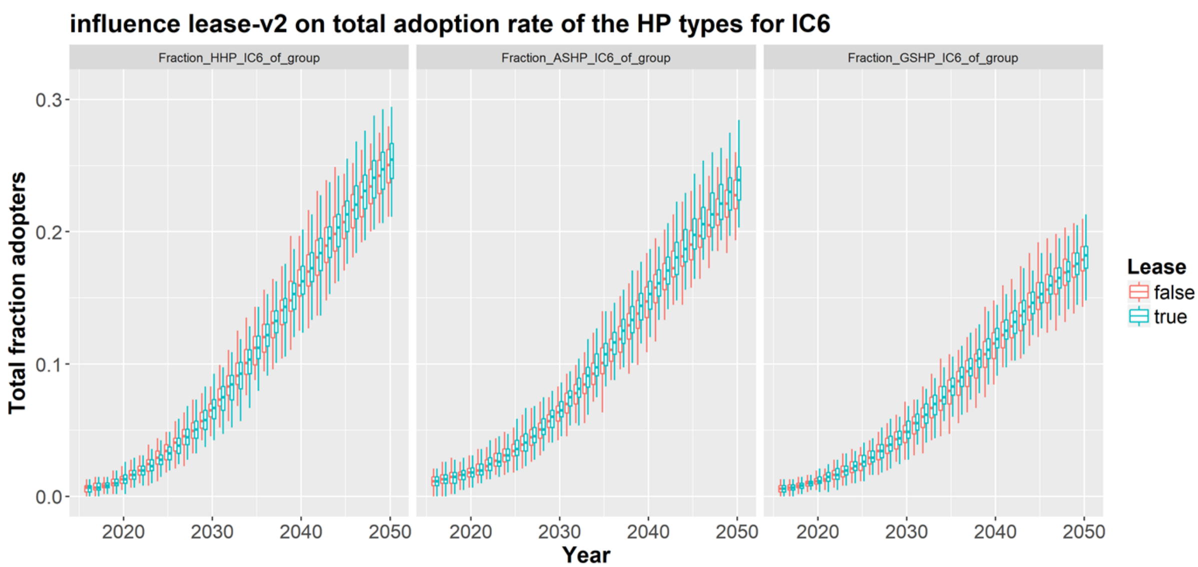


Figure 78: Adoption of the different HP types for income 6

C.4 Influence of 100% subsidy on the adoption rate

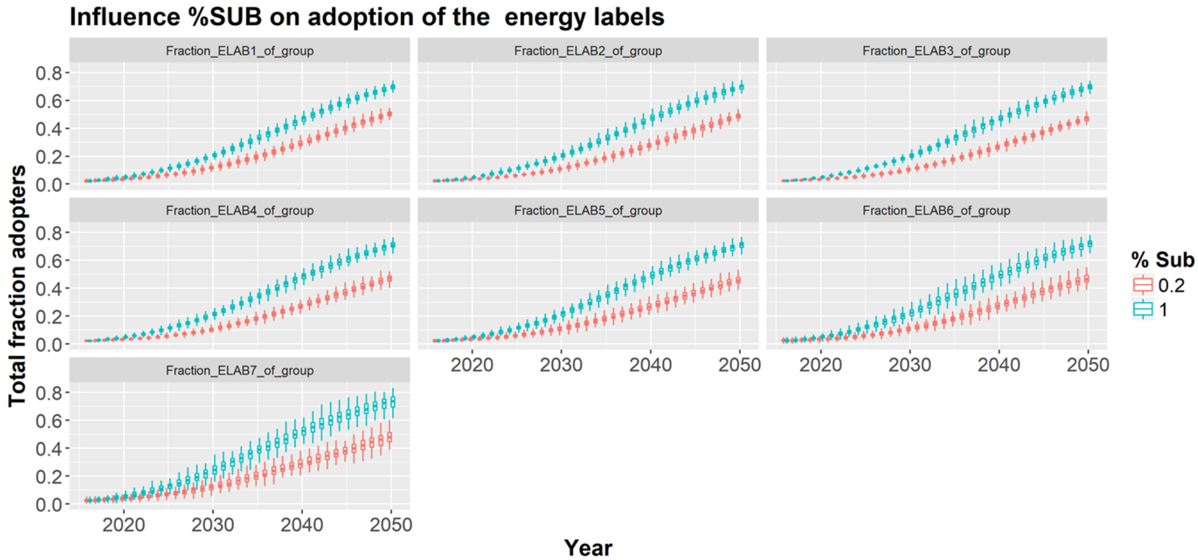


Table 35: The influence of a high subsidy level on the total adoption per energy label

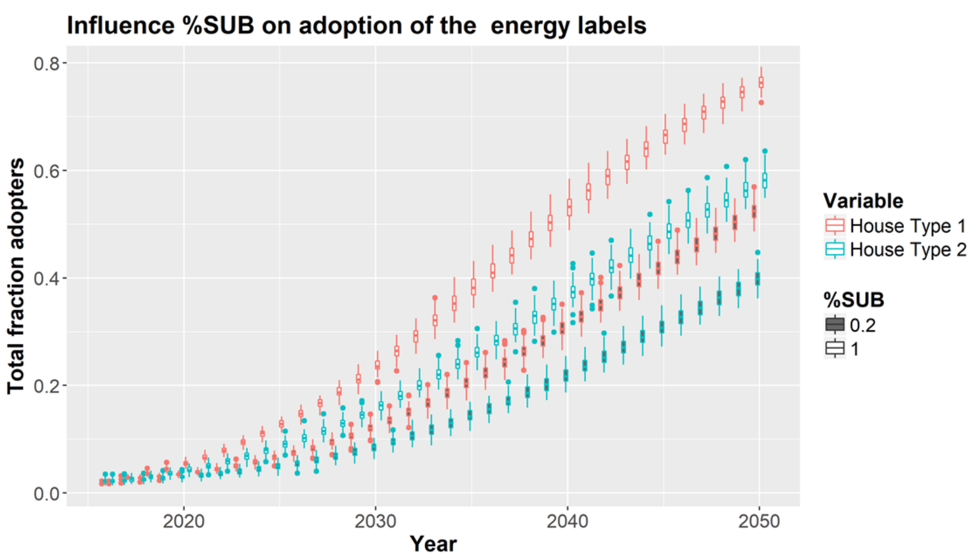


Figure 79: Influence high subsidy on the adoption per house type

C.5 Influence of the five scenarios

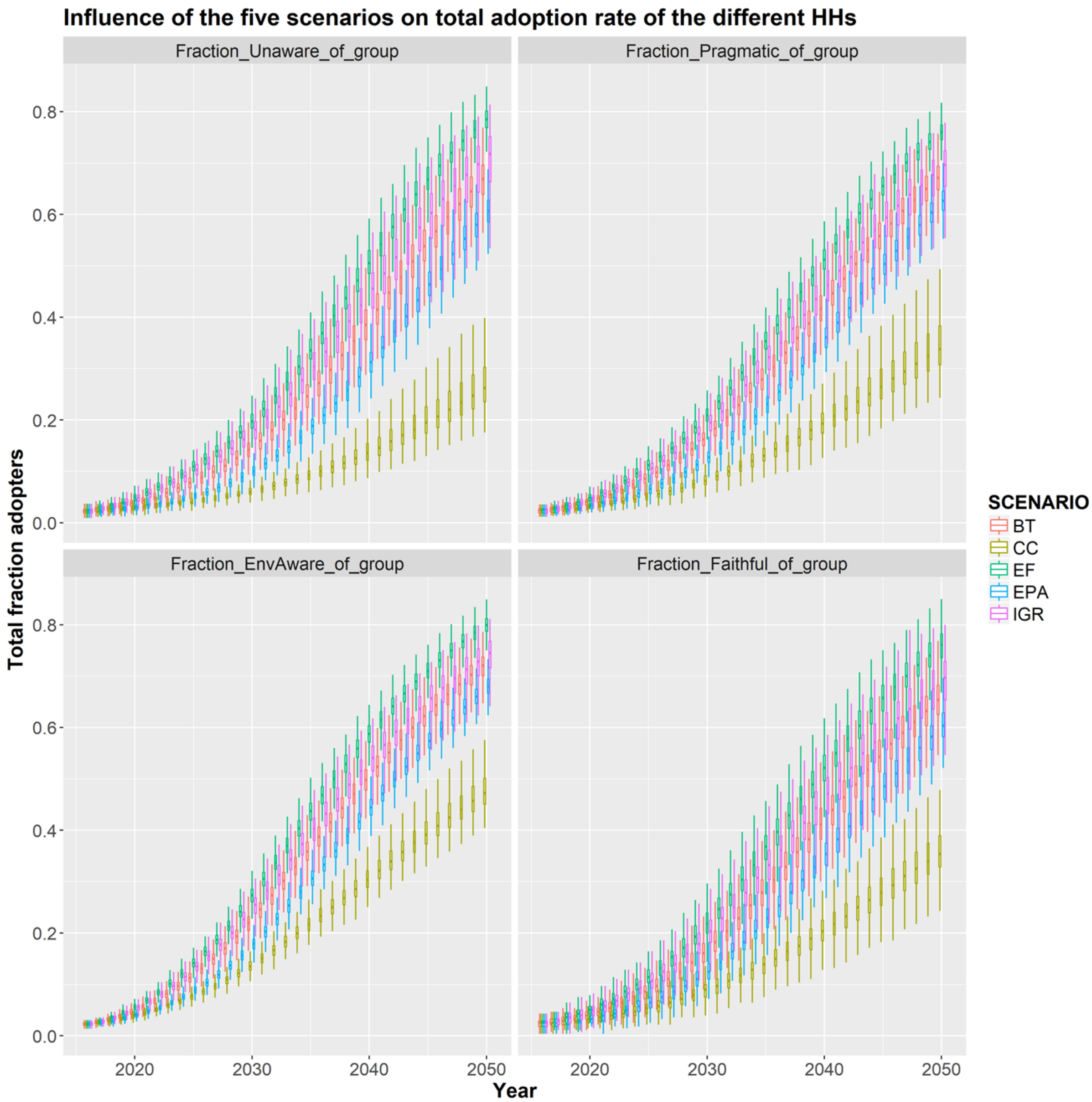


Figure 80: Adoption per household group for five scenarios

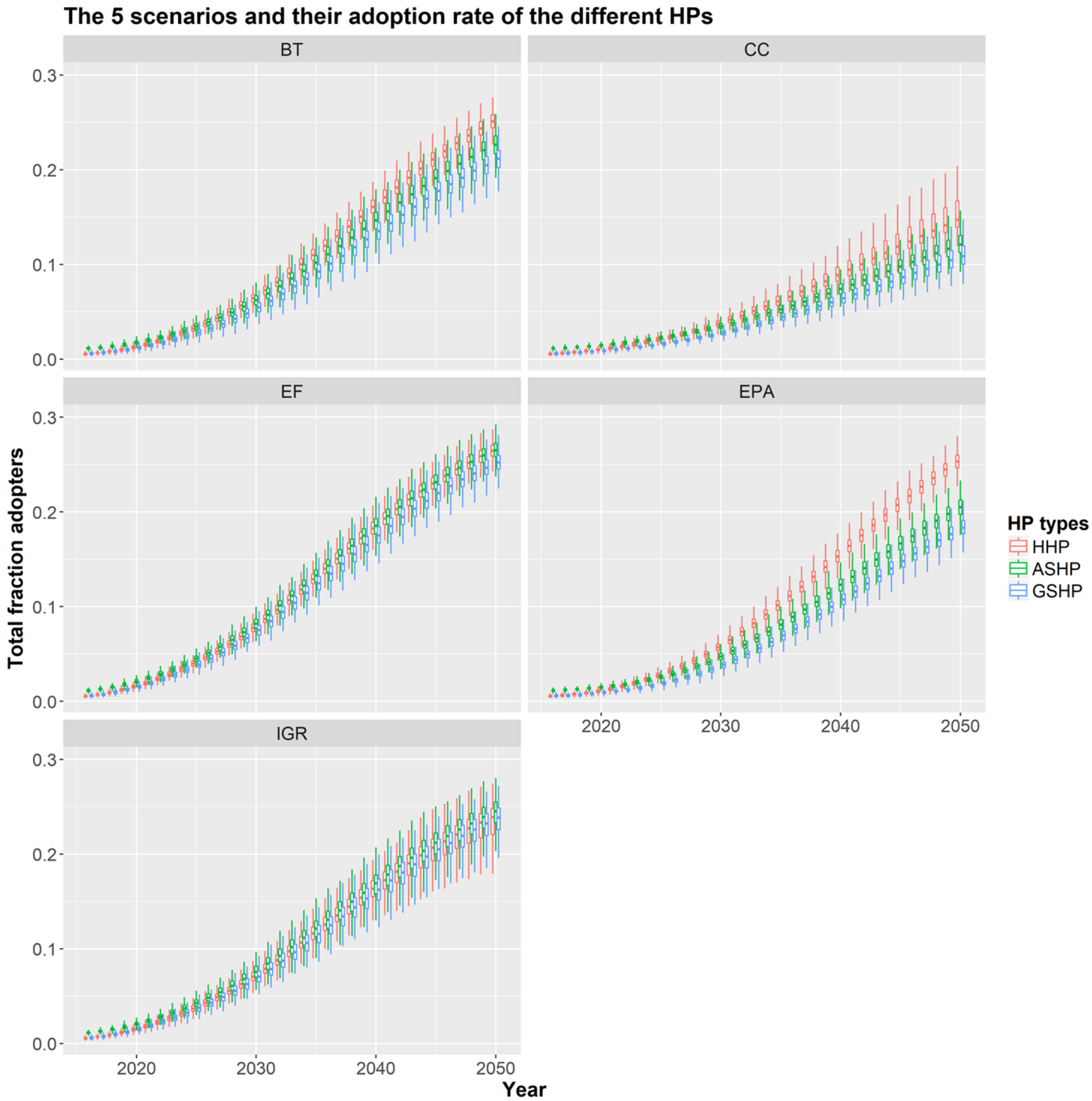


Figure 81: Heat pump adoption per scenario

C.6 Extra graphs DISC-B

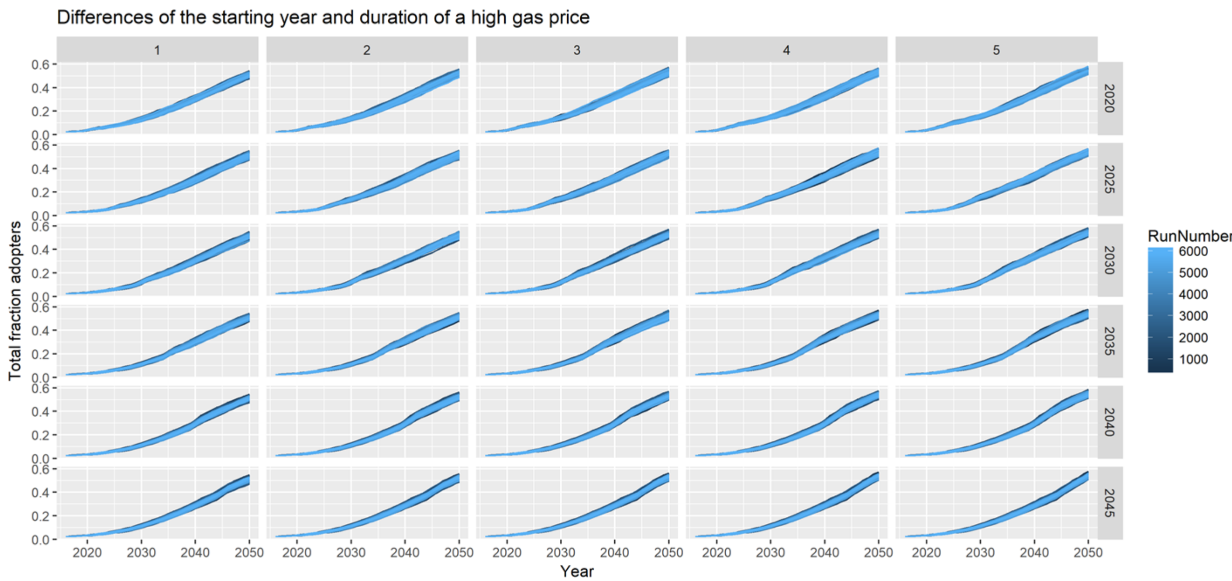


Figure 82: Adoption under different durations (x-axis label) and starting years (y-axis labels)

C.7 Extra graphs DISC-C

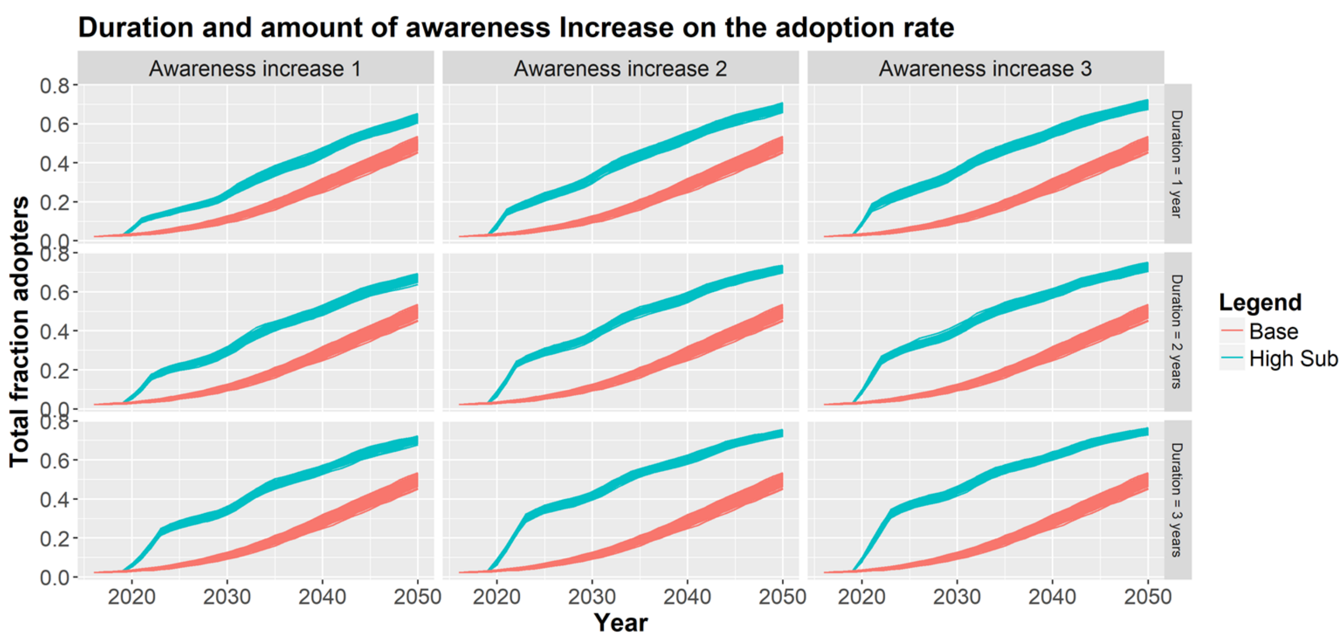


Figure 83: Influence of the awareness increase level and the duration of the high subsidy on for DISC-C

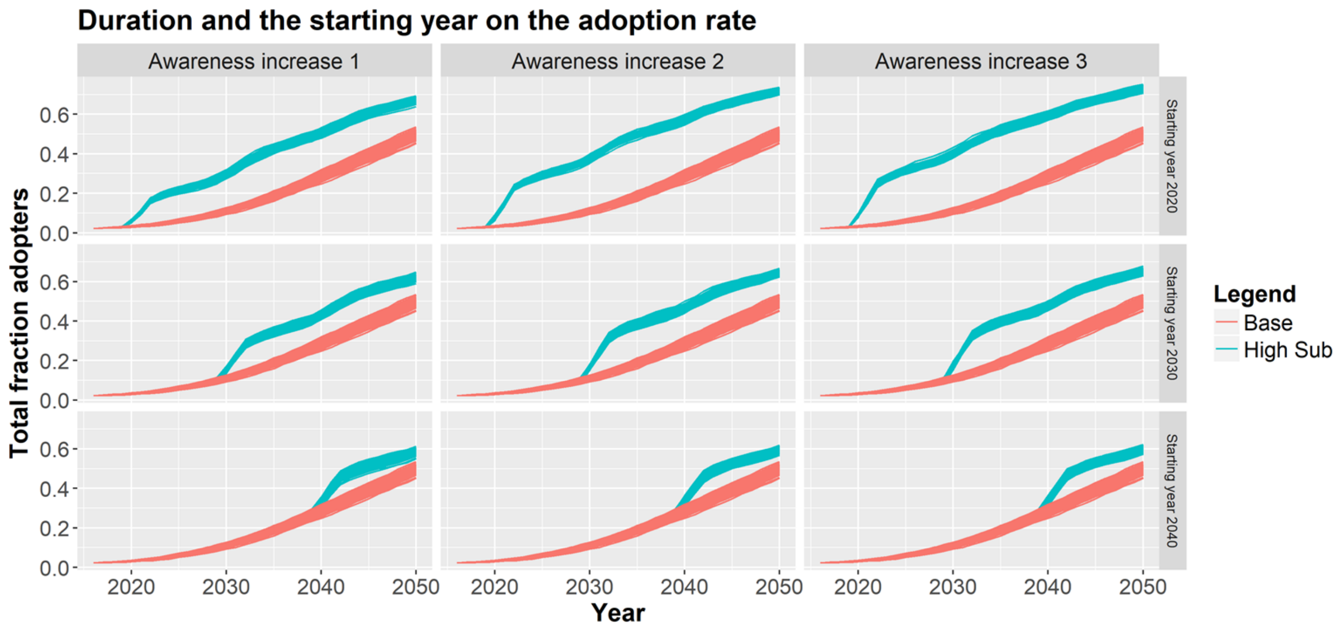


Figure 84: Influence of the awareness increase level and the starting year on the adoption with experiment DISC-C

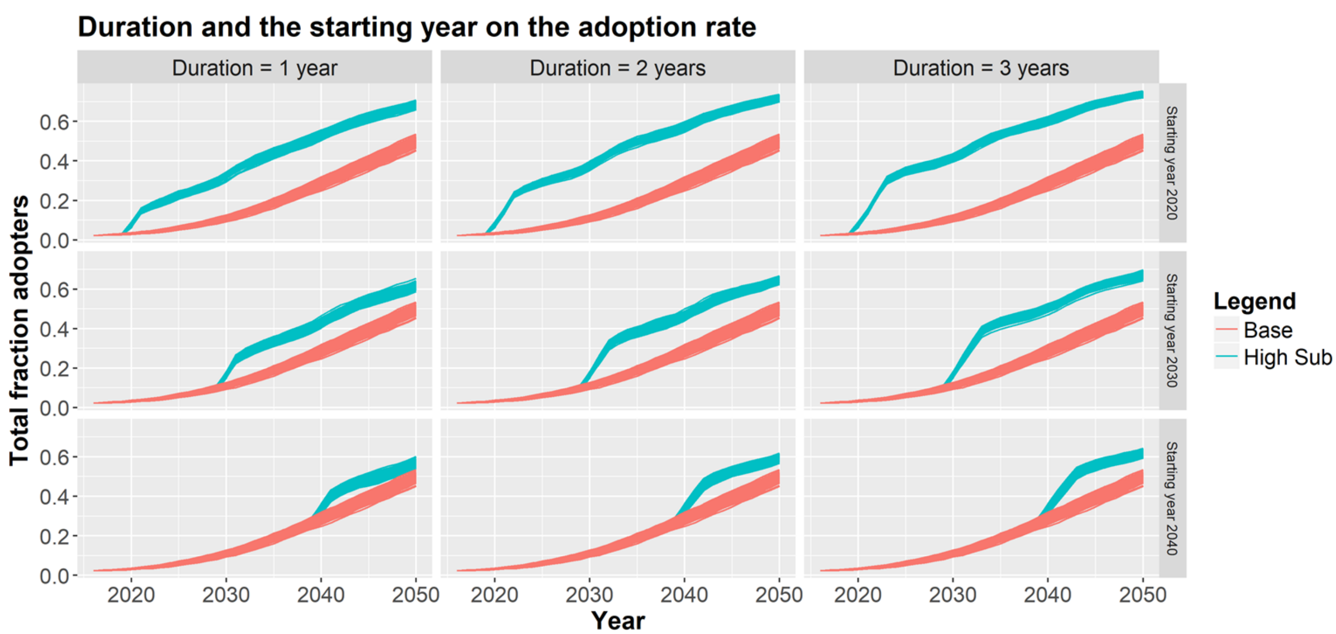


Figure 85: Influence of the duration and starting year on the adoption for experiment DISC-C

Appendix D: Sensitivity analysis

This appendix is a supplement for 8.2. Here all the plots for the sensitivity analysis are presented for the percent subsidized, gas price growth, initial gas price, initial electricity growth, the CO2 per kWh, the network costs, the experience parameter, the awareness, reason and resource check. The sensitivity was tested with a 10% increase and decrease for the integer variables. The Booleans were either on or off

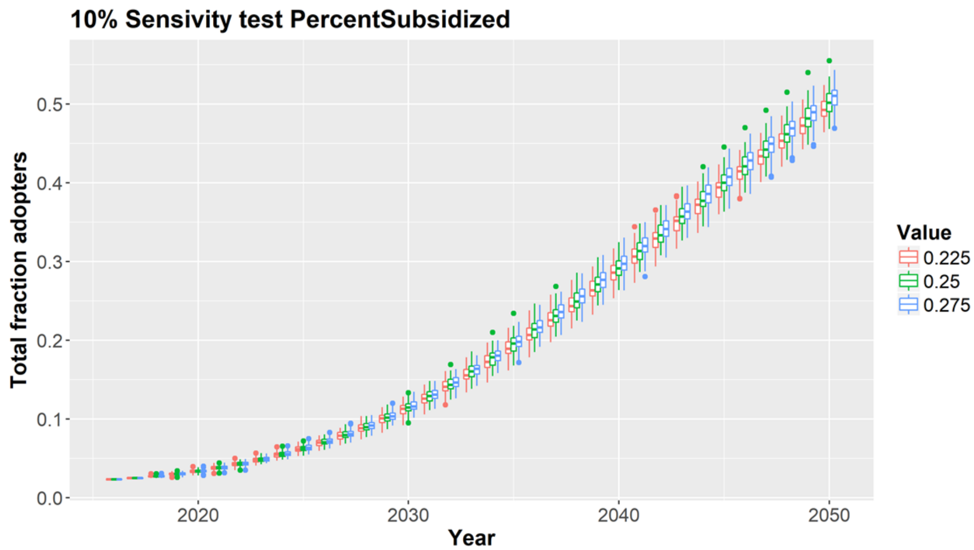


Figure 86: Sensitivity of the percent subsidized

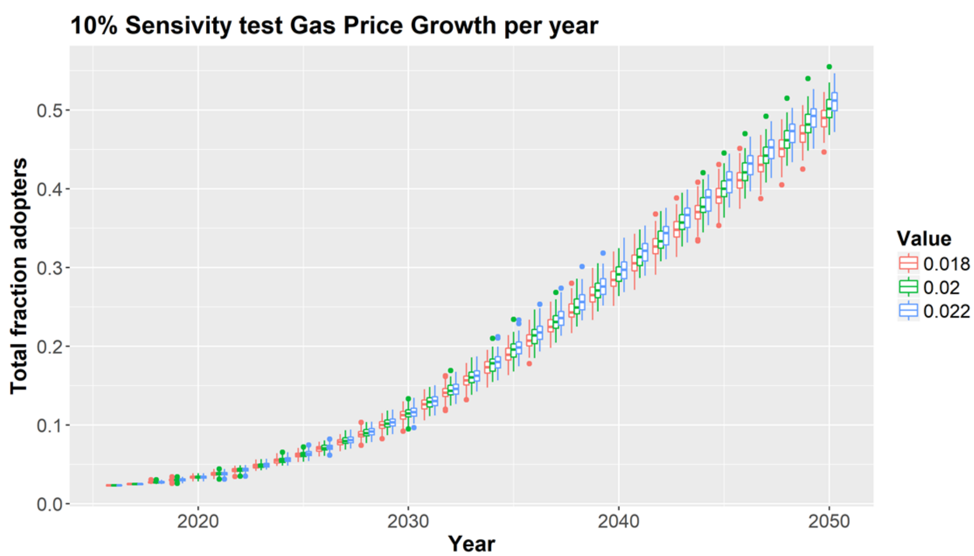


Figure 87: Sensitivity of the the gas price growth per year

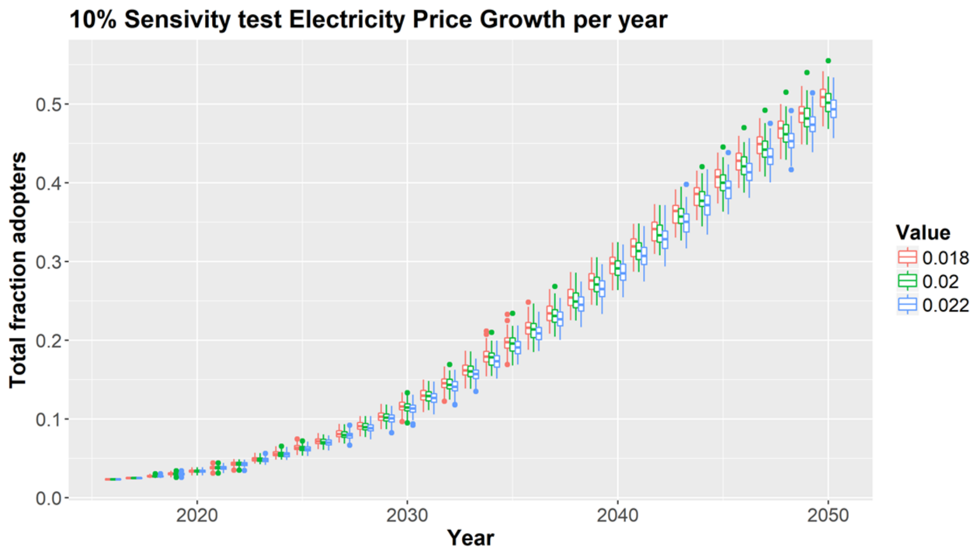


Figure 88: Sensitivity of the electricity price growth per year

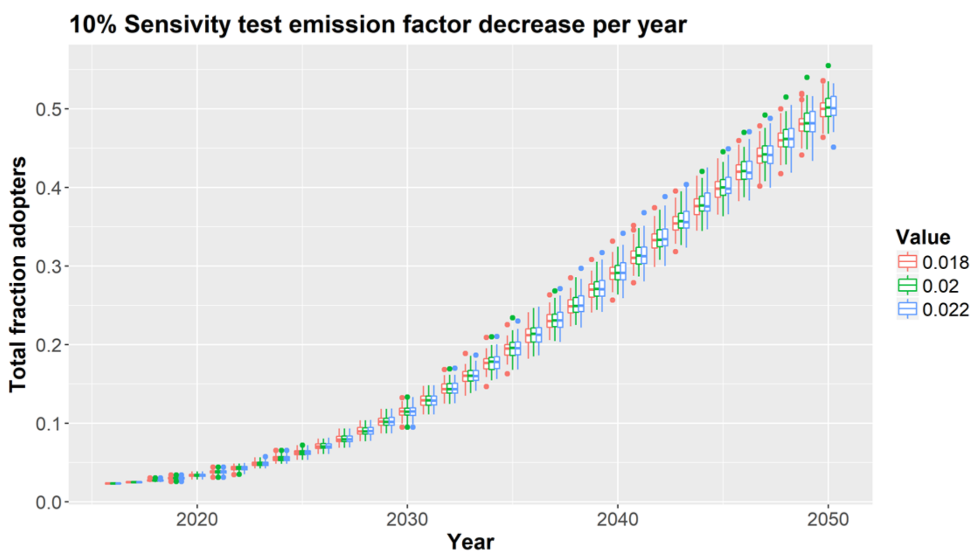


Figure 89: Sensitivity of the of the emission factor decrease per year

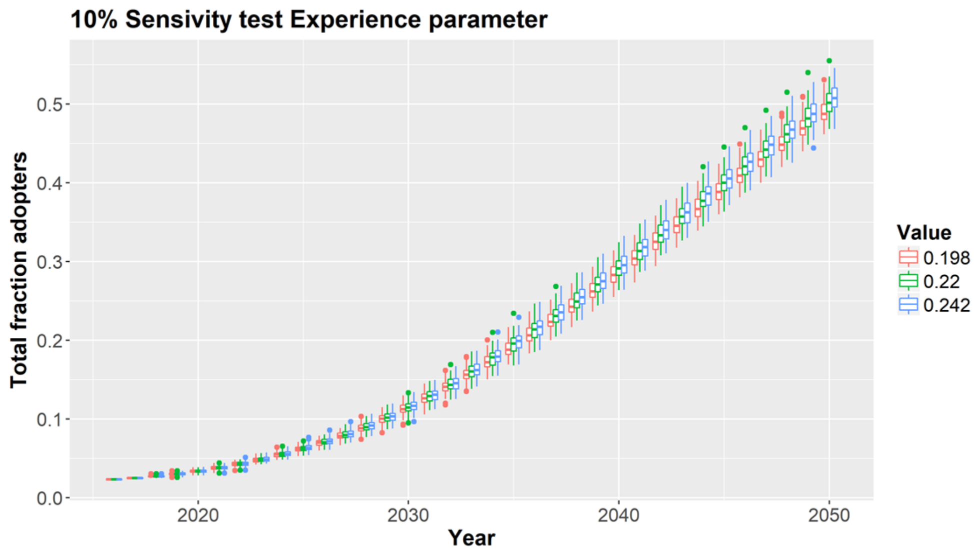


Figure 90: Sensitivity of the experience parameter

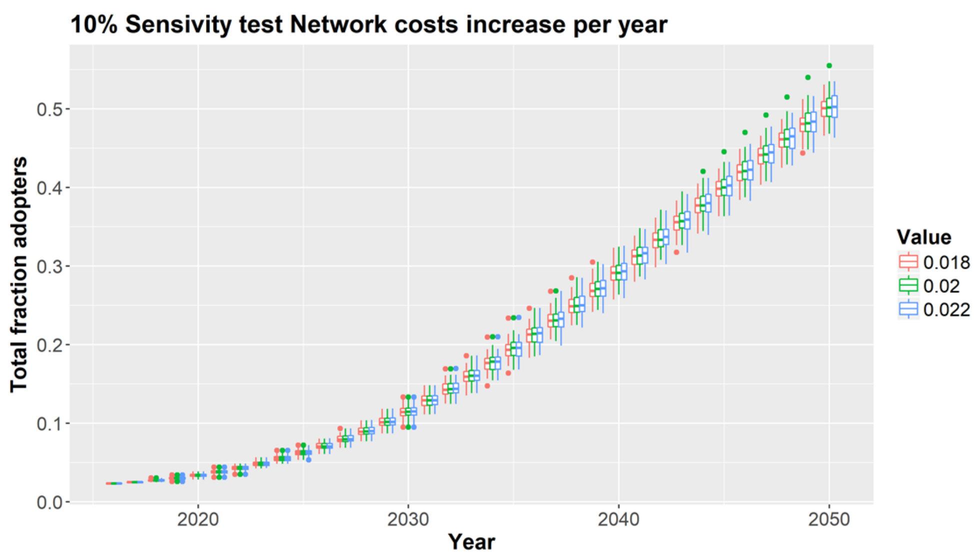


Figure 91: Sensitivity of the network costs

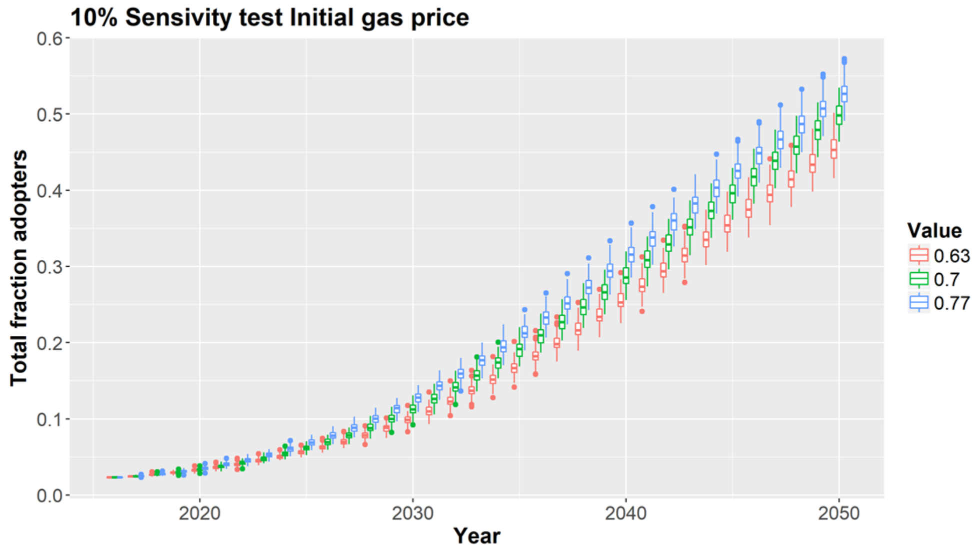


Figure 92: Sensitivity of the initial gas price

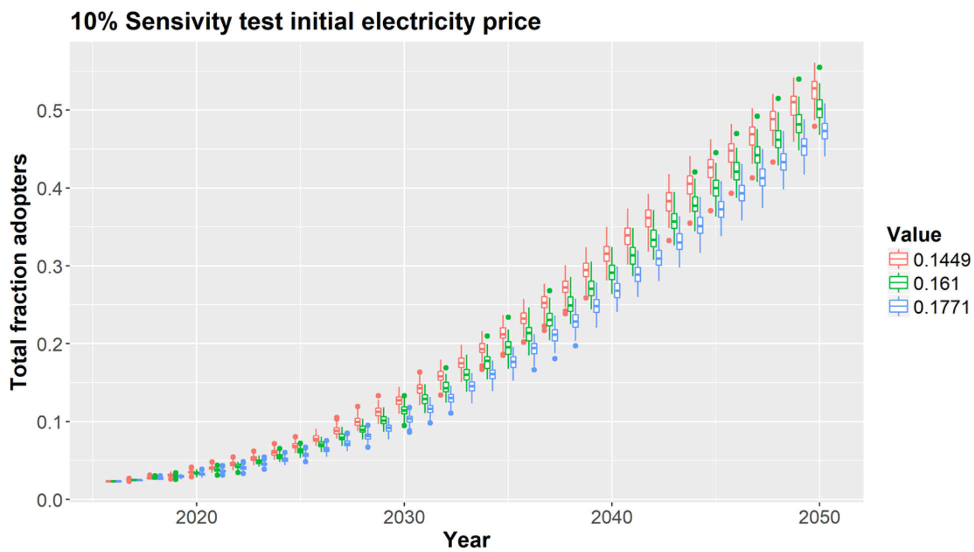


Figure 93: Sensitivity of the initial electricity price

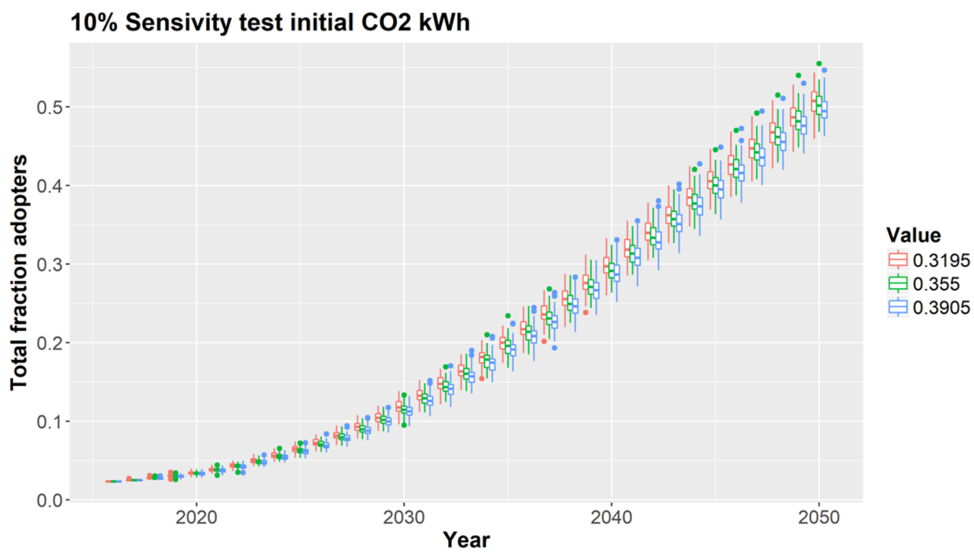


Figure 94: Sensitivity of the CO2 per kWh

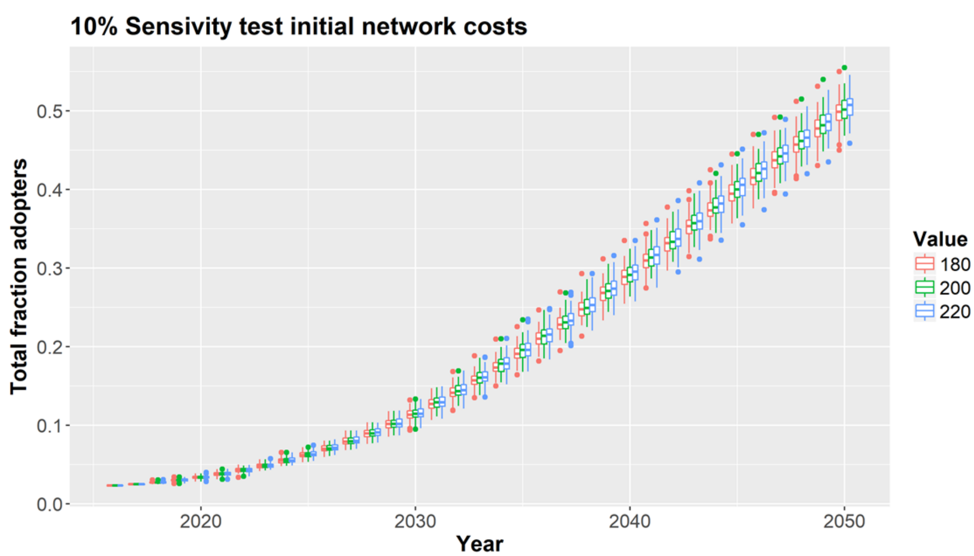


Figure 95: Sensitivity of the initial network costs

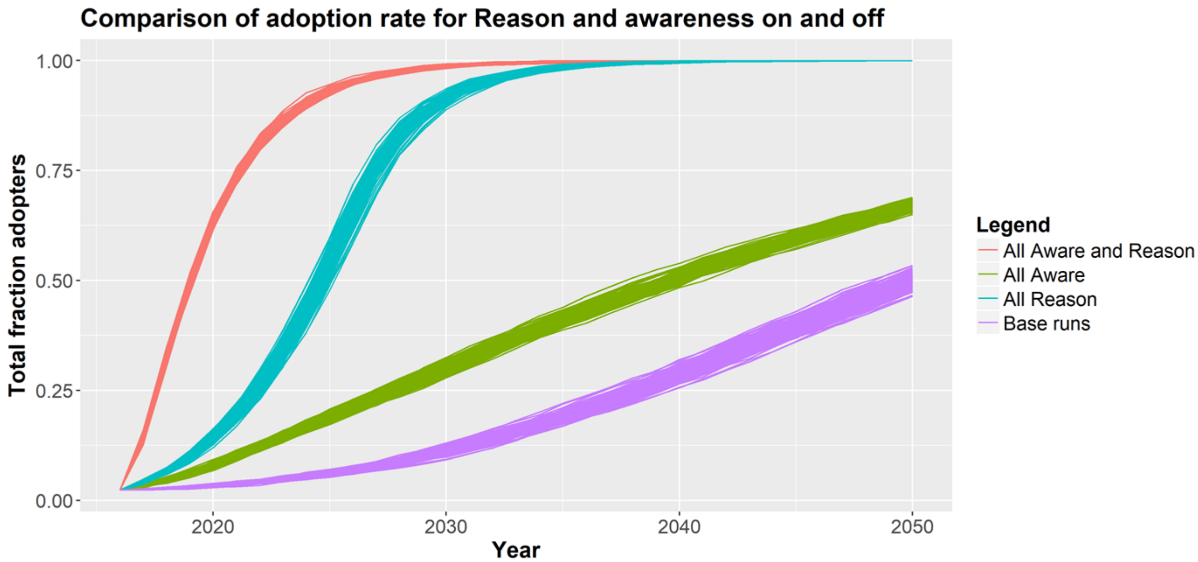


Figure 96: Sensitivity of the awareness and reason

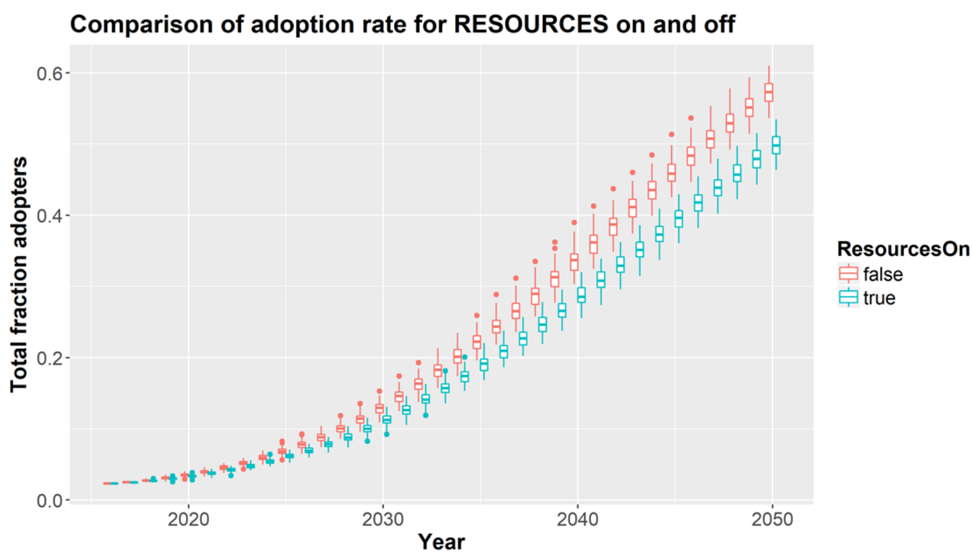


Figure 97: Sensitivity of the resources check