Decarbonising the Residential Space Heating Sector of the Netherlands in 2050 through Three Decarbonisation Pathways – Hydrogen Boilers, Hybrid Heat Pumps and Electric Heat Pumps

Kunal Chowdhury

Decarbonising the Residential Space Heating Sector of the Netherlands in 2050 through Three Decarbonisation Pathways– Hydrogen Boilers, Hybrid Heat Pumps and Electric Heat Pumps

by

Kunal Chowdhury

in partial fulfilment of the requirements for the degree of

Master of Science
in Sustainable Energy Technology
at the Delft University of Technology,
to be defended publicly on Tuesday August 26, 2020 at 3:00 PM.

Supervisor:	Prof. dr. ir. Kornelis Blok
Thesis committee:	Prof. ir. Kornelis Blok, TU Delft
	Prof. ir. P. G. Luscuere, TU Delft
	Prof. Ad van Wijk, TU Delft

This thesis is confidential and cannot be made public until August 26, 2020.

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

Acknowledgement

There were several challenges in defining the scope and methodology for this thesis, and great uncertainty regarding the energy system of 2050 in the Netherlands. I would like to thank Prof. Dr. Kornelis Blok for his guidance during the process of completing this thesis, whose inputs were crucial in providing the required direction through every phase of the project. I would like to thank the rest of my thesis committee as well, whose suggestions and recommendations provided valuable insight during the later stages of the writing process.

I would also like to thank my thesis committee, and also TU Delft, for enabling communication routes and distance-learning infrastructure during the unexpected coronavirus outbreak earlier in 2020 in a timely manner, which ensured that work on my thesis was not disrupted entirely, and without which, I would not have been able to proceed.

Finally, I would like to thank my friends and family, without whose support, none of this would have been possible.

Kunal Chowdhury

4738101

August 2020

Abstract

Residential space heating demand in the Netherlands is met by natural gas boilers in 93% of Dutch households. In order to combat global climate change and limit the increase in global average temperatures to below 1.5°C by the year 2050, the Netherlands will have to cut down its emissions across all sectors of human activity to nearly zero. The residential space heating sector accounts for majority of the emissions of the built environment, decarbonising this sector is key to eliminating greenhouse gas emissions and combating global climate change.

Decarbonisation of the residential heating sector can be achieved through multiple pathways. The aim of this thesis is to investigate which pathway would have the least cost to the end user in the year 2050. Three pathways have been selected, the all-electric pathway based on using heat pumps to meet space heating demand, the core hydrogen pathway based on meeting heating demand with end-use hydrogen boilers, and the hybrid pathway based on meeting heat demand with hybrid heat pumps.

Electricity supply in all three pathways will come mainly from solar photovoltaic energy and wind turbines and hydrogen will be produced by electrolysis of water, from renewable electricity. Hydrogen is assumed to be transported directly to end-user households using the existing natural gas transport infrastructure of the Netherlands, with adequate safety modifications, after being produced by dedicated offshore wind turbine capacity. Hydrogen is not produced at all in the electric pathway. First, the heat demand per household (space heat + domestic hot water) is determined for each of the five types of dwellings in the Netherlands. Annual energy cost per household is then determined from projected future electricity and hydrogen retail prices.

The installation of heat pumps will also involve renovations to the home to improve insulation levels in order to maximise the coefficient of performance, at additional cost to the end-user. The total annual cost per household of each pathway is then determined as the sum of the annual energy cost per household, the investment and installation cost of each device per household, and the annual maintenance cost. Total annual cost per decarbonisation pathway is the sum of the total annual cost per household for all houses in the Netherlands in 2050.

The annual cost per household varies widely depending on the values of electricity and hydrogen tariffs in 2050, the capital investment cost of each device, the level of household renovations required to improve household insulation levels, and the cost of investment in devices such as low temperature radiators. Annual costs vary among different types of dwellings, the smaller the dwelling, the smaller the required area to be heated. The annual cost per pathway was found to mainly have uncertainties regarding the device capital investment cost and electricity and hydrogen tariffs in 2050.

To reduce uncertainties in results, a scenario study was performed. The scenarios were constructed to account for the variations in device capital investment cost found in literature for electric and hybrid heat pumps, and the variations in energy tariff (electricity and hydrogen tariff) estimates for 2050. In five out of six analysed scenarios, the hydrogen boiler pathway was found to have the least annual costs in 2050, with electric heat pumps being the most expensive pathway in these scenarios.

Contents

Acknowledgement

Abstract

Table of Contents

1. Introduction, Research Questions and Motivation

Climate change is one of the greatest challenges facing humans in the twenty first century. In order to prevent permanent changes to the climate by anthropological forcing, countries have to combine their efforts in reducing greenhouse gas emissions to zero across all sectors of human activity. According to "Gas for Climate – An Optimal Role for Gas in a Net Zero Emissions Energy System" by Navigant, the built environment is a source of 36 percent of the greenhouse gas emissions of Europe. A 2018 report by PBL - "Technical and Economic Potential for Gas Free Built Environment in the Region Drechtsteden" (Technisch en Economisch Potentieel Aardgasvrije Gebouwde Omgeving Drechtsteden), stated that the Netherlands signed the Climate Agreement in Paris in 2015, which called for an 80 – 95% reduction in greenhouse gas emissions across all sectors by the year 2050, compared to 1990. [1]

In order to meet these requirements, Netherlands will most likely have to reduce carbon dioxide emissions in the built environment to near 0%, along with abating emissions from other sectors. The residential heating sector at present utilises natural gas for heating, the main source of greenhouse gas emissions in the built environment. According to the 2018 study by PBL, 95% of homes, shops, offices and buildings in the Netherlands are heated using natural gas boilers. To create a zero emissions heating sector for the built environment, natural gas needs to be replaced with renewable alternatives. Also, increasing extraction of natural gas from the Groningen gas fields has resulted in earthquakes in the Groningen region which have been increasing in severity with the increase in extraction. [1]

Prior studies, both in Netherlands, and in other countries, have explored the decarbonisation of the residential heating sector. Studies in the Netherlands were peformed by PBL in Drechtsteden (PBL 2018 – "Technical and Economic Potential for Gas Free Built Environment in the Region Drechtsteden") [1] and Utrecht (PBL 2018 – "Potential Costs and Climate-Neutral Built Environment in the Municipality of Utrecht" (Potentieel en Costen Klimaatneutrale Gebouwde Omgeving Gemeente Utrecht) [2]. The studies undertaken by PBL were performed over specific regions, not in a national context. They also did not include the possibility of utilizing hydrogen within the energy mix, as an alternative to heat pumps and electrification.

The present study considers three decarbonisation technologies – all-electric air and ground source heat pumps, hybrid heat pumps, and hydrogen boilers, and considers the Netherlands as a whole. To the best of [the writer's] knowledge, there have been no similar studies conducted in the Netherlands that have also included the use of green hydrogen (hydrogen produced via electrolysis using renewable electricity). The Netherlands is the second largest producer of Hydrogen in Europe, after Germany, as stated in the study undertaken by DNV GL - "Exploration of Hydrogen Infrastructure" (Verkenning waterstofinfrastructuur) - 2017 [3], including hydrogen in the Dutch energy mix may be crucial to achieving decarbonisation. The aim of this study is to expand on the theme of these two prior PBL studies and to derive indicative figures for the costs involved in achieving the same extent of deep decarbonisation for the entire Dutch heating sector. The results of the study undertaken by DNV GL are used as motivation to use the current natural gas transportation grid of the Netherlands to supply green hydrogen to households.

The present study aims to explore the economic and technical feasibility of implementing zero emissions technologies in the residential space heating sector of the Netherlands as a whole. The analysis will be done according to three possible technological pathways, namely decarbonisation using all-electric heating (heat pumps, either air source or ground source), decarbonisation using hybrid heat pumps, and decarbonisation using end-use hydrogen boilers. Energy supply in each scenario is 100% renewable energy based on solar photovoltaic energy and wind energy. Biomass will not be considered for the energy supply mix. Hybrid heat pumps are considered hydrogen-electric hybrids. Hydrogen will be considered as a direct energy carrier, for use in hydrogen-only end use boilers. The results of the gas grid analysis will be used for this study, the existing gas grid is largely suitable for hydrogen transport, as we will see in the chapter Future Hydrogen Production Costs and Speculative Prices.

Chapter 2 looks at prior studies that have been performed to decarbonise the residential heating sector in specific regions in the Netherlands, and also in other countries, such as the study performed by Imperial College to decarbonise the residential heating sector of the UK. Chapter 3 outlines the studies that formed the basis of calculating annual space heating demand per dwelling, selecting model inputs such as electricity tariffs, and the investment costs of heat pumps, hybrid heat pumps and hydrogen boilers for the present study. Chapter 3 also details the studies that formed the basis for selecting hydrogen tariffs, and the methodology of setting hydrogen tariffs is discussed. In Chapter 4, the possibility of utilizing hydrogen in the current natural gas grid of the Netherlands in 2050 is discussed. The annual cost per household in each pathway is presented and the factors that most affect the system cost in each pathway are discussed in chapter 5. In Chapter 6, the total annual cost of each decarbonisation pathway is presented, for different initial assumptions. Chapter 7 is the Discussion chapter, where sensitivity analysis is carried out for decreased hydrogen tariffs. In Chapter 8 is the Summary, and Chapter 9 is the Conclusion.

1.1 Research Questions

- What are the ways through which the residential heating sector of the Netherlands can be decarbonised?
- Which decarbonisation pathway could be achieved with the least cost to the end-user?
- What factors do the system cost rely on?
- What are the uncertainties regarding the annual cost of each pathway, and what are their impacts on overall cost?

2. Prior Work

First, the studies that have already been undertaken to decarbonise the space heating sector have been outlined, along with the important results from each study. These results are used as motivation to undertake the present study. Other studies have also been presented, covering the basis for calculating annual space heating demand per household, electricity and hydrogen prices, costs of heat pumps, hybrid heat pumps and hydrogen boilers and the costs of renovating households to improve their insulation grade. These studies have been presented in Model Inputs and Methodology. Further studies that have been carried out in order to determine the suitability of utilising the current Dutch gas grid to transport 100% Hydrogen. The chapter Future Hydrogen Production Costs and Speculative Prices details the calculation of the hydrogen tariffs for this study.

2.1 Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) Study for the European Union

A 2019 report published by the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) outlined the potential role of hydrogen in the future energy supply of the European Union as a whole. The study was devised as a 'roadmap' to establishing the use of hydrogen in the future energy portfolio of the European Union, for the purpose of maintaining security of energy supply with a high penetration of renewable energy technologies.

The study first modelled the general EU energy system for the year 2050, based on projections of renewable energy availability for the year 2050. The projections were based on sources such as the IEA '2-degree Celsius scenario' – the increase in global temperature by 2050 was limited to under 2 degrees Celsius. The energy generation mix was based on Enerdata's 'green scenario' and compared with the European Union's PRIMES model for the year 2050. After modelling, the market potential for hydrogen was identified through two scenarios for hydrogen – production from steam methane/ autothermal reforming, and production from electrolysis of water.

The study notes that space heating in the EU accounted for 15% of the total carbon dioxide emissions in 2015, with older buildings (75% of the EU's building stock is older than 25 years) making up 90 percent of these emissions. Improving household insulation levels to reduce energy usage would prove impractically expensive for these older buildings. To stop the use of natural gas to heat households, the study suggests the use of either electric heat pumps, or hydrogen boilers.

The use of electric heat pumps alone would cause a large difference in energy demand between summer and winter months – generators would have to be built that stay idle in the summer, and only operate during winter, as noted in the FCU study. The study also found that heat pumps are benefited by improved insulation levels, further increasing their installation and investment cost in older buildings.

To decarbonise the building heating sector in the most cost effective manner, the study recommends the use of hydrogen, combined with the use of electrical heat pumps. A further benefit of utilising hydrogen, as mentioned in the study, is that hydrogen can be adopted in the energy generation mix with minimal modifications to the current energy transport infrastructure. Thus, the future energy system based on hydrogen can be run in a largely similar manner to current energy markets.

The study singled out the case of the Netherlands modifying the gas transport network to accommodate high calorific gas from Russia and Norway, upgrading from low calorific Groningen gas. The cost of these modifications were included in the final energy tariff, an approach that the study recommends for the future uptake of hydrogen for space heating. On comparing the auto thermal/steam methane reforming pathway with that of the electrolysis pathway, it was stated that electrolysis will ultimately reduce Europe's reliance on fossil fuels, reduce overall energy costs in future, and will not require additional investment in carbon capture and storage technologies. The study does note, however, that the electrolysis pathway would require higher initial investments. [4]

2.2 Regional studies in Netherlands - Drechtsteden

Transitioning to zero emissions in the residential heating sector may be achieved in more than one way. The ideal transition would be one carried out at minimal cost to the end user. Studies analysing the feasibility of introducing zero emissions technologies in the residential heating sector have been carried out over small areas, for example, the study carried out by Folckert van der Molen et.al for the region of Drechtsteden. [1] The study was carried out to limit greenhouse gas emissions in the year 2035 by 90% of the 1990 emissions level (and to reduce natural gas consumption by 90% compared to 2015 levels) and aimed to determine the feasibility of implementing alternative space heating technologies through more than one pathway, presenting multiple options.

The different pathways for achieving decarbonisation were compared on the basis of minimising the social cost, i.e. only the pathways which could be implemented at the lowest social cost would be chosen. The modelling was carried out on the VESTA MAIS model. The heat sources for both studies were heat from Combined Heat and Power plants, geothermal energy, waste heat from industry and heat from biomass plants. Five scenarios were presented, one reference scenario with unchanged policy and technical measures except for current rates of technology improvement till 2015, and 4 scenarios to reduce natural gas use by 90% of 2015 levels by the year 2035. The scenarios were evaluated based on four sensitivity parameters, which were the future development of technical investments, the upgrading of building insulation, ratio between peak and base loads and the buildings sharing heating within a neighbourhood.

The results of this first phase were further examined by observing the effects of individual changes of four policy measures, followed by a scenario in which the emissions targets are achieved with a combined policy. The devices used for heating in the Drechtsteden study, based on the scenario, were a combination of district heating, all-electric heat pumps and natural gas-fired boilers. The study showed that by 2035, deep reduction in carbon emissions of the residential space heating sector of the region of Drechtsteden, (by 90% of the 1990 levels of carbon emissions), could be achieved by utilising all-electric heat pumps and district heating (elaborate on how much each pathway cost in the study)

In the first scenario (energy saving measures + individual heat pumps), the total annual social cost for Drechtsteden were 452 million euros, higher than the baseline scenario of ‘business as usual’, mainly due to renovation costs to improve building insulation levels, and high investment cost of heat pumps. In the second scenario (energy saving measures + individual heat pumps + central heat pumps in buildings with good insulation), the total annual social cost was 430 million euros, with a large part of the annual costs being the investment cost of the heat network for connecting central heat pumps. [1]

2.3 Regional studies in Netherlands - Utrecht

A similar study to the Drechtsteden study was undertaken by Ruud van den Wijngaart et al. of PBL, for the region of Utrecht. [2] The Utrecht study aimed to determine the feasibility of implementing alternative space heating technologies through more than one pathway, presenting multiple options. The different pathways were compared on the basis of minimising the social cost, i.e. only the pathways which could be implemented at the lowest social cost would be chosen.

Modelling was carried out on the VESTA MAIS model. The collective heat sources for both studies were heat from Combined Heat and Power plants, geothermal energy, waste heat from industry and heat from biomass plants. Four transition scenarios were outlined, and further analysed on four sensitivity factors. The devices used for heating in the Utrecht study, based on the scenario, were a combination of district heating, all-electric heat pumps and gas-fired boilers, identical to the Drechtsteden study. In addition, the study also explored the use of a hybrid heat pump instead of the all-electric heat pump in the scenarios where heat pumps were used. The Utrecht study also mentions that hydrogen could be used in place of natural gas in hybrid heat pumps, but no analysis for this situation was carried out.

The results of the Utrecht study with respect to the use of hybrid heat pumps in the space heating sector showed some advantages of utilizing hybrid heat pumps. First, hybrid heat pumps may be more favourable to use instead of, or in combination with all-electric heat pumps, as hybrid heat pumps can be used in homes with relatively poorer insulation than electric heat pumps, representing a lower initial investment cost (investment costs are halved, according to the study) and wider applicability of hybrid heat pumps. The hybrid heat pumps halved the gas consumption in well insulated homes. It notes that the hybrid heat pump option may be viewed as an intermediate to the all-electric heat pump option. The study indicates that the hybrid pathway to decarbonisation would be cheaper to implement than the all-electric pathway. [2]

2.4 Other Studies to Decarbonize the Dutch Residential Heat Sector

On 12 February 2020, TNO released a report that reviewed the findings of several prior studies in the Netherlands to decarbonise residential space heating demand. The studies reviewed in the report were CE Delft (2016), Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – Update 2016 (A climate-neutral heat provision for the built environment – Update 2016), CE Delft (2017), Net voor de Toekomst – Achtergrondrapport (Grid for the Future – Background report), Quintel (2015), Beelden van een CO2-arme Nederlandse samenleving in 2050, Verkenning voor de Raad voor de Leefomgeving en Infrastructuur (Images of a CO2-low Dutch society in 2050, Explorations for the Council of the Living Environment and Infrastructure) and Ecofys (2016), Kwantificering van toekomstscenario's voor de gebouwde omgeving (Quantification of future scenarios for the built environment). These reports are in Dutch, with no English translations available, so, the review by TNO is used as the reference.

The study notes that in general, the technologies considered for 2050 in all the studies reviewed were a combination of electric heat pumps, hybrid heat pumps running on green gas or another renewable gas, boilers that run with renewable or green gas, heat networks, heat-cold storage, and solar thermal energy. The study outlined one of the general findings across studies to be that heat demand was highest when green gas was used to the highest extent. This was attributed to the levels of household insulation – households using electric heat pumps would also have to minimize heat demand by improving household insulation levels. Improved insulation levels for hybrid heat pumps would also lead to a greater amount of annual heat demand being met by the electric heat pump component. The two studies by CE Delft do not consider electricity demand due to heating and household appliances, these costs are considered in the Ecofys and Quintel studies.

The study noted the similarities amongst the reviewed studies, and the differences. The main similarity was that green gas would play an important role in most scenarios. In addition, the share of green gas in the final energy portfolio would depend on the domestic availability and price of green gas in 2050. The study also noted that electrification was increased substantially in all the investigated scenarios. The share of electricity in meeting annual heat demand for residences is dependent on the price of the alternative heating options, including hydrogen in 2050. Solid biomass would have almost no role by 2050. Scenarios considering heat networks would depend almost entirely on geothermal and waste heat sources.

According to the review report by TNO, the main factor on which the future energy system of the Netherlands (for the residential sector) will be the availability of renewable gases, either green gas or hydrogen. Not all of the investigated scenarios in the listed studies are optimistic about the use of hydrogen for residential heat. Hydrogen storage was mentioned as a particular application for hydrogen in the residential heat supply of the Netherlands in 2050, however, the study noted that research and development was required to realize this. [5]

2.5 Studies in other countries – Imperial College UK

A study done by Goran Strbac et al. at the Imperial College, UK, (Analysis of Alternative UK Heat Decarbonisation Pathways for the Committee on Climate Change - August 2018) [3] analysed three alternative pathways for the UK to transition its space heating sector to have zero percent emissions by the year 2050. The analysis was an economic analysis to determine the lowest cost pathway to transition to a zero emissions heating sector.

For the first phase, the three pathways were based on – (1) Hydrogen, with the use of hydrogen boilers at the site of the end-user, (2) Electric pathway, where heat pumps were used, and (3) Hybrid pathway, with the use of hybrid heat pumps. The gas used in the hybrid pathway was either hydrogen, or green gas (gas produced from biomass). The modelling was done on the Integrated Whole Energy System model developed at Imperial College. Each core decarbonisation pathway was analysed further according to ten sensitivity factors, or 'uncertainties'.

The second phase was to analyse the economic performance of different combinations of each of the core pathways – three regional decarbonisation strategies, two district heating strategies, and replacing hybrid heat pumps with micro Combined Heat and Power plants. The study assumed the centralised production of hydrogen from autothermal reforming combined with carbon capture and storage for production of hydrogen from natural gas as the default technology, supplemented with hydrogen produced by electrolysis.

Biogas and bioenergy, solar photovoltaic energy, wind energy and nuclear energy were the low carbon energy generation technologies considered in the study. The study considered energy storage (thermal, electricity and hydrogen storage) and also included the impact of using hydrogen within the existing natural gas distribution network, and included the costs involved in modifying the existing network to carry enough hydrogen in order to ensure security of supply. This additional cost also adds to the cost of the core hydrogen pathway.

The study by Imperial College showed that complete decarbonisation of the heating sector of the UK is possible using either all-electric heat pumps, hybrid heat pumps, or hydrogen boilers, with energy supply being fully renewable. The study notes that the green hydrogen pathway is the most expensive to implement, however, the prices are highly uncertain due to the limited hydrogen economy in the UK. Green hydrogen is produced via electrolysis, with the electricity coming from renewable energy sources, thus being completely emissions free.

The cost of each pathway varies depending on the extent of decarbonisation desired. The cost of each decarbonisation pathway is directly dependent on the extent of decarbonisation desired. The study also notes that the hybrid pathway is the cheapest across all levels of decarbonisation. This finding agrees with the results of the Utrecht study, which showed that hybrid pathways are cheaper than fully electric ones. In addition, the study notes that the hydrogen pathway is the most sensitive to the price of fuel, when compared to the other two scenarios. Finally, the study indicates that the present natural gas infrastructure of the UK can be repurposed at minimal additional cost, to transport 100% hydrogen in the gas distribution network. [6]

In order to decarbonise the residential heating sector of the Netherlands by 2050, cues and indicative results can be taken from the studies mentioned in this chapter. The FCH-JU study showed some broad trends regarding the uptake of hydrogen for the European Union as a whole. Broad decarbonisation will most likely need to be achieved through a combination of renewable energy generation technologies, energy storage technologies, and flexibility technologies, all of which will require additional investment for the future. Either heat pumps (electric or hybrid) or hydrogen boilers can be used in households to decarbonise the residential space heating sector. In order to be cost effective, it is likely that a combination of electric heat pumps and hydrogen boilers will be the optimum solution. Older buildings will also likely need renovations to the insulation to improve their insulation label, particularly for the electric heat pump scenario, to maximise on the coefficient of performance.

The results of the Dutch regional studies and the study by Imperial College indicate that decarbonisation of the residential heating sector of the Netherlands as a whole can be achieved using all-electric heat pumps, hybrid heat pumps, or hydrogen boilers, with energy supply being from a combination of renewable energy and non-renewable technologies such as solar photovoltaic generation, solar thermal generation, wind power, nuclear energy, geothermal power and biomass.

The residential heat infrastructure of the UK is similar to that of the Netherlands, based almost entirely on natural gas boilers at the end user site, with pipelines to transport the gas from extraction point to end-user sites. With these similarities and with similar levels of decarbonisation being needed for the Dutch residential heating sector, it is likely that results for the Dutch residential heating sector would be similar to those of the UK. The similarities also indicate that the most likely choice of decarbonisation technologies for the Netherlands in 2050 will be all-electric heat pumps, hybrid heat pumps, and end-use hydrogen boilers. Each technology varies on the basis of investment, installation and maintenance costs. These will be further analysed in the chapter Model Inputs and Methodology.

3.1 Model Inputs and Methodology

This chapter discusses the methodology adopted for the present study, and the inputs used for modelling, excluding the hydrogen tariffs, whose selection has been detailed in the next chapter. The sources used for model inputs have also been discussed, with the relevant conclusions being used in this study. Modelling was performed in MATLAB in order to calculate the annual costs per household, for each insulation grade. The model uses meteorological data, housing data and assumptions, investment and maintenance cost assumptions for each device, insulation assumptions and home renovation cost data as inputs, and provides the annual cost per household for each decarbonisation pathway as output. First, the methodology of the study is detailed, under 'Model Construct'.

3.1 Model Construct - Three pathways

For the present study, decarbonisation of residential heat will be investigated through three pathways, for three different decarbonisation technologies. The three pathways are the core Hydrogen pathway, the all-electric pathway, and the hybrid pathway. Electricity generation in all pathways will be through the combination of solar photovoltaic and wind energy, supplemented with grid strengthening technologies and electricity storage, to make the energy supply 100% renewable.

The current energy system in the Netherlands is privatized, with transmission and distribution of energy being undertaken through a regulated retail market, energy tariffs are set in such a way that the energy generation companies are able to recover the cost of generating energy without the tariffs being oppressively high to the end consumer. The energy generation system of 2050 is assumed to be governed in the same way, for the purpose of the present study.

The electricity price may be determined from the Levelized Cost of Energy of the total energy system, and by including the cost mark-up required to cover administrative and other expenses faced by the energy generation companies. Also to be considered are the costs of the transmission and distribution grid for electricity, in centralised generation. The variable costs for most renewable energy sources such as solar PV and wind are mainly the operation and maintenance costs, as the fuel costs are zero for both. As will be detailed in subsequent sections, the Levelized System Cost of electricity production in the presented studies includes the Levelized Cost of electricity generation, transmission, storage and curtailment.

The price of hydrogen can be obtained by analysing the investment costs for hydrogen electrolysers, and from the price of the electricity that is used for the process. As a starting point, it is assumed that there exists a dedicated renewable hydrogen production facility in the northern part of the Netherlands, utilizing offshore wind energy from the North Sea. As there is no carbon released during electrolysis using clean electricity, there is no need for carbon capture and storage for the space heating sector. Also needed are the costs of transmitting hydrogen through pipelines in the hydrogen core and hybrid pathways. Hydrogen is not used at all in the all-electric pathway.

Investigating annual costs through rigid pathways is limiting as most scenarios investigated in previous studies are comprised of a combination of several technologies. Those studies utilised energy system models with system interdependencies taken into account. Without access to such models, it is difficult to determine the possible composition of an energy generation system with multiple technologies. In the 'Discussion' Chapter, this is expanded further, annual cost are calculated based on the cheapest technology for each dwelling type.

In addition, technologies such as hydrogen fuel cells have not been considered as an application for hydrogen in the built environment for the Netherlands in 2050. The aim of the present study is to determine the cheapest way to decarbonise the space heating sector of the Netherlands – fuel cells utilise hydrogen to produce electricity rather than heat, heat is produced as a by-product (combined heat and power). In addition, hydrogen boilers have an efficiency greater than 0.95, whereas electrolysis through PEM fuel cells is expected to have an efficiency of greater than 0.7 by 2030, according to a 2018 report by TKI Nieuw Gas. Hydrogen boilers have also currently entered the market, while fuel cells are mostly still in development, making hydrogen boilers a better choice for investigation in the present study.

As seen in other reports, 93% of Dutch residences use natural gas boilers for their space heating and hot water demand. Large-scale heat networks are not currently widespread and the costs of their expansion are not easily available or clearly divided. There are also significant uncertainties in the number of dwellings that the heat network would ultimately expand to, and what the costs of that expansion are. In addition, heat networks require geothermal and waste heat sources to run, as seen in the literature earlier, the technical and economic potentials of which are also highly uncertain by 2050 in the Netherland. The uncertainty of expansion and the price uncertainties are the reasons for heat networks to not be considered in the present study, for the Netherlands in 2050. This is expanded upon in Chapter 7.

3.1.1 Hydrogen pathway

The core Hydrogen pathway is based on the application of end-use hydrogen boilers at consumer premises to decarbonise heat demand. Heat demand per household in the present study takes into account only the annual demand for space heating and annual domestic hot water demand. Capital cost of the hydrogen boiler and installation costs are the main investments to be made by consumers in this pathway. The costs per household will be in the form of an annual bill for each type of dwelling in the Netherlands. The total bill is the sum of the investment costs, the installation costs of each heating device, the amount spent on hydrogen gas for space heating annually, the costs of improving household insulation levels, and the annual boiler maintenance costs. All investment costs are annuitized over the lifetime of the device, as detailed in the section “Annuitization of Investment Costs”.

3.1.2 Electric pathway

In the all-electric pathway, heat demand (space heating + domestic hot water) is met by end-use electric heating appliances such as air and ground source heat pumps. This pathway will not use hydrogen. As heat pumps cannot heat water to higher than 55°C, domestic hot water demand will be met by electric resistive heating. This is discussed further under “Determining Hot Water Demand”. Capital cost of the heat pump and installation costs are the main investments to be made by consumers in this pathway. In addition, as heat pumps require superior insulation levels to maximise their COP, the cost of home renovations to improve the insulation label is also taken into account.

The costs per household will be in the form of an annual bill for each type of dwelling in the Netherlands. The total bill is the sum of the investment costs, the installation costs, the amount spent on electricity for space heating annually, the device maintenance costs and the cost of renovations to improve insulation. All costs are annuitized over the lifetime of the device. Widespread utilization of heat pumps will lead to an increase in electricity peak load and potentially, and increase in electricity tariffs, this is expanded in the Discussion chapter. All investment costs are annuitized over the lifetime of the device, as detailed in the section “Annuitization of Investment Costs”.

3.1.3 Hybrid pathway

This pathway is based on the application of combining the use of gas and electric heating systems in a single device, i.e. hybrid heat pump (HHP), to meet residential heating demand (space heating + domestic hot water). The gas heating system in the Hybrid system uses hydrogen to eliminate emissions from gas. Water is heated rapidly using gas firing, for sudden changes in demand, especially when it is very cold, while the heat pump will provide base load heat. Domestic hot water demand will be met by the hydrogen boiler component entirely.

Capital cost of the hybrid heat pump and installation costs are the main investments to be made by consumers in this pathway. Costs will vary based on whether the hybrid systems are purchased in an add-on configuration or as a packaged system as well. Improving household insulation levels will also be required. The costs per household will be in the form of an annual bill for each type of dwelling in the Netherlands. The total bill is the sum of the investment cost, the installation costs, the amount spent on hydrogen gas and electricity for space heating annually, cost of improving household insulation levels, and the device maintenance costs. All costs are annuitized over the lifetime of the device, as detailed in the section "Annuitization of Investment Costs".

3.1.4 Modelling Approach and Formulae Used in Modelling

Table 3.1 - Abbreviations Used

Abbreviation	Meaning	Unit
ΔT	$Indoor - Outdoor\ temperature\ difference$	K
ΔT_{DHW}	$Temperature\ lift\ for\ domestic\ hot\ water\ demand$	K
$t_{heating}$	$Heating\ season$	Hours
U	$Building\ thermal\ transmission\ coefficient$	W/m^2K
S	$Building\ surface\ area$	m^2
V	$Building\ volume$	m^3
q	$Hourly\ air\ exchange\ rate$	$\frac{m^3h^{-1}}{m^3}$
rec	$Fraction\ of\ heat\ recovered\ from\ outgoing\ air$	
c_{air}	$Specific\ heat\ capacity\ of\ air$	$\frac{Wh}{m^2K}$
c_{water}	$Specific\ heat\ capacity\ of\ water$	$\frac{kWh}{KgK}$
$COPHP$	$Coefficient\ of\ Performance - Heat\ Pump$	-
$COPHHP$	$Coefficient\ of\ Performance - Hybrid\ Heat\ Pump$	-
Eff	$Hydrogen\ Boiler\ Efficiency$	-
n	$Insulation\ Lifetime$	Years
T	$Device\ lifetime$	Years
$Energy_{Heating}$	$Annual\ space\ heat\ demand$	kWh
W_{Daily}	$Daily\ hot\ water\ demand$	Litres/day
$Energy_{DHW}$	$Annual\ domestic\ hot\ water\ demand$	kWh
$P_{electricity}$	$Electricity\ tariff$	Euros/kWh
$P_{Hydrogen}$	$Hydrogen\ tariff$	Euros/kWh
$Cost_{Device}$	$Annual\ investment\ and\ installation\ cost\ of\ each\ device$	Euros
$Cost_{cap}$	$Capital\ Cost\ and\ installation\ cost\ of\ each\ device$	Euros
r	$Rate\ of\ inflation$	%
Ins	$Insulation\ cost\ per\ unit\ area$	Euros/m^2
$Cost_{maintenance}$	$Annual\ maintenance\ cost\ per\ device$	Euros
$Cost_{Insulation}$	$Annual\ insulation\ cost\ per\ unit\ area$	Euros/m^2
$Cost_{Investment}$	$Annual\ investment\ cost\ per\ household\ per\ scenario$	Euros
$Heat_{electric}$	$Annual\ heating\ cost\ per\ household\ for\ heat\ pumps$	Euros
$Heat_{hydrogen}$	$Annual\ heating\ cost\ per\ household\ for\ hydrogen\ boilers$	Euros
$Heat_{hybrid}$	$Annual\ heating\ cost\ per\ household\ for\ hybrid\ heat\ pumps$	Euros

The following formulae have been used in modelling the three decarbonisation pathways in MATLAB. The model calculates the annual heat demand for each type of dwelling based on meteorological conditions for the year 2050. The model gives the annual cost per household for each scenario.

- $$\left(Energy_{Heating} = 0.001 * \Delta T * t_{heating} * \left[\left(\frac{S}{V} * V * U\right) + \left(V * \left(q * (1 - rec)\right) * c_{air}\right)\right]\right) \text{ kWh} \qquad (i)$$

This formula calculates the annual heat demand for the different types of dwellings based on the dwelling dimensions, surface area, volume, insulation level (denoted by heat transfer coefficient U), and the length of the heating season. The factors that control building heat demand have been explored in subsequent sections.

- $$Energy_{DHW} = \frac{W_{Daily} * 365 * c_{water} * \Delta T_{DHW}}{Heat\ losses\ through\ pipes\ and\ tank\ walls} \qquad (ii)$$

- This formula calculates the annual domestic hot water demand for the different types of dwellings based on the number of people per dwelling, daily hot water demand per person per dwelling, and the temperature lift required. The assumptions for domestic hot water demand have been explored in subsequent sections.

- $(Heat_{electric} = P_{electricity} * \frac{Energy_{Heating}}{COPHP}$ Euros $\qquad (iii)$
  This formula calculates the annual cost of heating per household using fully electric heat pumps which takes the coefficient of performance of the heat pump into account

- $(Heat_{hydrogen} = P_{Hydrogen} * \frac{Energy_{Heating}}{Eff}$ Euros $\qquad (iv)$
  This formula calculates the annual cost of heating in households using hydrogen boilers, taking into account the boiler efficiency with respect to HHV

- $\left(Heat_{hybrid} = \frac{Energy_{Heating}}{COPHHP}\right)$ Euros $\qquad (v)$
  Calculates the annual cost of heating in households using hybrid heat pumps, taking the coefficient of performance of the heat pump into account

- $(Cost_{Device} = \frac{r*Cost_{cap})}{(1-(1+r)^{-T})})$ Euros/year $\qquad (vi)$
  This formula annuitizes the capital and installation cost of each device

- $\left(Cost_{Insulation} = \frac{r*Ins)}{(1-(1+r)^{-n})}\right)$ Euros/m^2 $\qquad (vii)$
  This formula annuitizes the insulation cost per unit area

- $(Cost_{maintenance} = (0.05) . (Cost_{Device}))$ Euros $\qquad (viii)$
  Maintenance cost taken as 5% of device cost

- $(Cost_{Investment}\ (electricity\ scenario) = Heat_{electric} + Cost_{Device} + Cost_{Insulation} + Cost_{maintenance})$ Euros $\qquad (ix)$
  Total annual cost per household when using electric heat pumps in 2050

- $(Cost_{Investment}\ (hydrogen\ scenario) = Heat_{electric} + Cost_{Device} + Cost_{maintenance})$ Euros $\qquad (x)$
  Total annual cost per household when using hydrogen boilers in 2050

- $(Cost_{Investment}\ (hybrid\ scenario) = Heat_{electric} + Cost_{Device} + Cost_{maintenance})$ Euros $\qquad (xi)$
  Total annual cost per household when using hybrid heat pumps in 2050

Determining the energy costs is dependent on the type of decarbonisation technology, and whether the requirement is space heating or domestic hot water demand. These are detailed further in subsequent sections.

3.2 Inputs for Future Electricity Prices

Electricity prices in 2050 will be comprised of the same components as current electricity tariffs, namely production costs, distribution costs and network costs and VAT. For the present study, VAT and other taxes are not considered. The energy generation system for 2050 is assumed to be based entirely on renewable energy. An average electricity and hydrogen tariff will be considered for each scenario, as electricity tariffs can vary widely during the course of a day and time-of-use is not considered in the present study.

The price of electricity per unit (kWh or MWh) is estimated from literature, by assuming that solar photovoltaic and wind energy are the main energy sources in combination with technologies such as energy storage, (battery storage) in order to increase the flexibility of the system. The costs of strengthening the grid to account for increased renewable energy generation are still highly uncertain and they have been included as an increase in electricity tariffs – expanded further in the Discussion chapter. The levelized cost of energy of the overall renewable energy generation system gives a starting point for electricity prices. The supply tariff will have to include the retail margin, for electricity retail companies to recoup their costs.

Currently, the total electricity or natural gas supply tariff charged to households per kWh in the Netherlands includes electricity and gas transmission and distribution costs using the existing gas transport grid for gas, and using the national electricity grid for transporting and distributing electricity, plus government taxes, as found by examining the current energy tariff structure for the Netherlands, through agencies such as CBS Statline. The levelized cost of energy of the energy system of 2050 will need to be added to the cost of electricity distribution, to determine the final electricity tariff charged to the consumer. The final electricity tariff charged to the consumer thus includes the production costs, distribution costs, and network costs.

3.2.1 Study for a 100% Renewable Energy System for the World

In a study by Finland's LUT University and the Energy Watch Group, a 100% renewable energy system was designed and modelled for the year 2050, for the entire world, based on climate agreements and the need to reduce global carbon emissions to zero. The study was performed over nine regions of the world – Europe, North America, South America Middle-East and North Africa, Sub-Saharan Africa, Eurasia, SAARC, Northeast Asia, and Southeast Asia.

In the study, renewable energy generation methods considered were solar photovoltaic, wind turbines, hydropower, geothermal and bio energy. Storage was divided into short-term (Li-ion batteries, pumped-hydro storage), medium-term and long term (power-to-gas) storage methods. The study also mentioned technologies that were used to improve flexibility and efficiency of the system – power-to-gas, heat pumps at individual and district levels (considered power-to-heat in the study), electric heaters, and steam turbines.

For Europe, the energy supply by the year 2050 was found to be a combination of solar energy, wind energy, hydropower, and synthetic natural gas generated from electricity (for hydrogen) and bio-methane, to satisfy the power, heat and transport sectors, among other sectors. Hydropower installations were not assumed to increase from present values. Solar photovoltaic generation made up 62% of the total electricity generated, becoming the lowest cost source of electrical energy, while wind energy accounted for 32% by 2050. Solar energy dominates in southern Europe, while wind energy generation is more common in Northern Europe.

Heat supply would come from waste-to-heat Combined Heat and Power plants, biomass based district heating and individual heating at the household level. Energy storage makes up 18% of total electricity demand in 2050, 83% of which is provided by batteries. In a regional sense, Southern Europe will require, on average, greater storage capacities to accommodate the greater solar energy generation. Heat storage provides 30% of the annual heat demand, through technologies like power-to-gas (40%) and Thermal Energy Storage (40-60%). Power-to-gas stores electricity as hydrogen, which is presumably used to provide heat energy via combustion.

Due to the energy generation system being based mostly on renewable sources of energy with little to no fuel costs, the system cost for 2050 is mainly dependent on the capital investment (CAPEX). The Levelized Cost of Electricity of the 100% renewable energy based system was found to be 50 – 60 €/MWh, while the Levelized Cost of Heat was found to be 47 €/MWh. The study notes that the Levelized Cost of Electricity for a 100% renewable energy system is lower than that of the current energy system (83€/MWh) based on fossil fuels when negative externalities of fossil fuel usage are taken into account. The designed 100% renewable energy system reduced the greenhouse gas emissions of the power, heat, transport and desalination sectors to zero. [7]

3.2.2 Study for a 100% Renewable Energy System for Europe

In the study 'The Benefits of Cooperation in a Highly Renewable European Electricity Network' by Schlachtberger et al., a 100% renewable energy system for the year 2050 was designed and modelled for Europe. Energy Generation was assumed to be a combination of wind energy, solar photovoltaics, hydropower, pumped hydro storage, batteries and hydrogen storage units. The study aimed to find an optimized energy system for Europe in 2050 based on constrains of energy generation, grid expansion, and energy storage.

Analysis of the energy system for the European Continent was done by assuming two levels of grid interconnectedness between countries – limited interconnectedness and economically optimal interconnectedness. Higher levels of grid interconnectedness will result in lower levels of required energy storage, as the geographical spread of the grid will neutralise the effects of synoptic variations of wind, and the geographical differences in available solar radiation.

In the study, the costs of transmission grid expansion are assumed to be a function of the length of transmission line, at 650 euros/kW for every kilometre of transmission line required, across Europe. Maintenance costs were taken as 2% of the investment cost per kilometre. The study also assumed batteries (LiTi) for short term (6 hours) storage, and hydrogen for long term (168 hours, or 1 week) storage. Capital cost of hydrogen storage was taken in the study to be 8.4 euros/kWh and capital cost of LiTi battery storage was taken as 144.6 euros/kWh.

Using a continent-wide transmission grid, and assuming the optimal level of grid interconnection, wind energy will generate 65% of the total energy in 2050, in Europe, hydropower will generate 15%, solar PV 16%. The share of solar radiation increases to 36%, when limited grid interconnection is assumed, with daily battery storage becoming necessary in this scenario. The study notes that countries like the Netherlands will need to use significant shares of their offshore wind generation potential.

The study found the Levelized Cost of Energy to be €65/MWh (optimum interconnectedness) and €84/MWh (limited interconnectedness), for four scenarios of grid expansion. The system with levelized costs of €65/MWh would require 9 times the grid line volume as compared to the present grid. Transmission investments made up 12% of the total cost. In the 'compromise' scenario, the grid line volume was expanded by four times, with larger shares of solar PV, hydrogen, and battery storage required. Losses in the grid are also taken into account as constraints during modelling. The cost of this scenario was 68 euros/MWh.

These measures would result in a 95% decrease in greenhouse gas emissions from 1990 levels. The study also notes that while grid expansion will lead to lower overall system costs and less energy storage, grid expansions are not particularly popular with the public, the economically optimum levels of grid expansion according to the study, are not particularly realistic scenarios. The study also did not consider the expansion of electricity distribution grids within countries. The study also did not investigate the effect of other economic sectors on the cost of the energy generation system. [8]

3.2.3 Stanford Study for a 100% Renewable Energy System Worldwide

In September 2017, Jacobson et. Al. conducted a study to transition 139 countries that contribute 99% of global greenhouse gas emissions to 100% renewable energy by 2050. The study found that the decarbonisation methods avoid a global increase of average temperatures of 1.5 degrees Celsius. The study takes into account the cost of electrical energy storage and the losses to the grid, matching supply and demand at every point in time. The study found that the LCOE for the renewable electricity generation system of the Netherlands in 2050 would be 78.9 euros/kWh, and 85.7 euros/kWh including the cost of storage, across all sectors (taken as 8 dollar-cents or 6.8 euro-cents/kWh). [9]

3.2.4 Study of a Single Hybrid Heat Pump in a Dutch House

According to "The role and potential of a hybrid heat pump in an existing Dutch house" by Bruno Bekhuis, electricity and gas tariffs were calculated based on future cost projection scenarios by ECN for electricity wholesale prices. These prices are lower than the electricity retail price per unit of electricity. The difference between the present retail and wholesale prices was used to markup the future wholesale prices. Finally, the cost of "Opslaag Duurzame Energie (ODE)", the Energy Tax and the VAT. ODE and VAT were assumed to be constant, but energy taxes were decreased for electricity and increased for natural gas, based on figures in "Klimaatberaad. (2018). Voorstel voor hoofdlijnen van het Klimaatakkoord (Tech. Rep.)". The electricity wholesale price for 2050 was found to be 0.060 euros/kWh and the electricity tariff (wholesale price + retail markup + ODE + VAT + Energy Tax Shift) = 0.156 euros/kWh, with energy supply for the heating system being 100% renewable. [10]

3.2.5 Study investigating the use of Hydrogen in the Dutch Electricity System

A 2020 study by Mathias Berger, David Radu, and Karolina Ryszka investigated the use of hydrogen in the Dutch electricity system for decarbonisation to 49%, 75% and 99% with respect to 1990 emissions levels. Power-to-gas, hydrogen and synthetic methane storage, and battery storage were the balancing and storage technologies used. Power generation was assumed to be centralized, along with power system operation. Electricity imports are also factored in, with the constraint that power generation matches demand at every point in time in the model. The study considered hydrogen fuel cells instead of hydrogen boilers, at the end-user site.

The study found that deploying battery storage, hydrogen storage, fuel cells, and electrolysers for hydrogen production, was more economically favourable than increasing renewable energy generation capacity, when emissions reductions of 99% with respect to 1990 levels are desired. For this scenario, the study found that solar PV and offshore wind turbines saw the maximum increase in built capacity. The average electricity price in this scenario was 82 euros/MWh, if electricity imports were allowed.

The study also investigated the effects of achieving a 99% emissions reduction if electricity imports were not allowed. The average electricity price in this scenario was 110 euros/MWh. According to the study, if electricity imports are allowed, wholesale import prices are comparatively lower, with up to 10% of the electricity demand being met by cheaply imported, emissions-free electricity. If imports are stopped, the demand has to be met by renewable electricity which is more expensive than the imported electricity. The study also noted that electricity spikes were much higher in this scenario compared to when imports are allowed, implying the need for more generation capacity. [11]

3.3 Setting Future Electricity Tariffs

From the studies outlined in the previous sections of this chapter, it becomes clear that electricity supply tariffs for the consumer are dependent on the energy generation portfolio, the energy storage methods, and technologies used to strengthen the grid to accommodate increased renewable energy generation.

The interactions of these agents in supplying energy to match the demand will determine the cost of energy generation. In the Netherlands, the supply of energy, both electricity and natural gas, is carried out through retail companies, connecting the energy producers to the end consumer. The energy retail tariff will therefore be higher than the cost of energy generation, to account for the costs incurred by the retail companies in supplying energy to the consumer.

For the present study, the electricity generation system of the Netherlands in 2050 is assumed to be 100% renewable energy based, similar to the generation portfolios outlined in previous studies. As with hydrogen tariffs, there is a high degree of uncertainty regarding future electricity production costs, which will depend on the energy generation technologies and the methods used to strengthen the grid in the case of increased renewable energy generation, to tide over the inherent intermittences in supply of solar and wind energy.

For the purpose of the study, several assumptions regarding future electricity production costs have to be made. It is first assumed that the electricity tariff at every household is flat throughout the year. This assumption will be addressed in the Discussions section. The electricity production cost will be determined by the overall energy generation mix, consisting of solar photovoltaics, onshore and offshore wind turbine installations, and power to gas combined heat and power plants, and energy storage (battery or hydrogen storage). Power-to-gas combined heat and power plants will use excess grid electricity to produce hydrogen for storage, which can be used to provide energy (electricity or heat) during shortages. Also included are grid transport and distribution costs.

The levelized cost of solar photovoltaics and wind energy is useful in providing a base line for the levelized cost of electricity for the 100% renewable energy generation system for the Netherlands in 2050 as assumed for the present study. The final levelized cost cannot be determined by simply adding the levelized cost of energy of solar photovoltaics and wind energy. The specific energy generation technologies and portfolio analysis are outside the scope of this study and are difficult to determine for a future energy system. Only the retail electricity tariff is needed as an input for modelling purposes, which is based on the levelized cost of electricity of the system.

In the study conducted by Finland's LUT for a worldwide, 100% renewable energy system, it was found that 94.6% of Europe's electricity would come from solar photovoltaics, and onshore and offshore wind turbines. The Levelized System Cost of Electricity of such a system was found to be €54MWh, including the levelized cost of storage, the levelized cost of curtailment, and the levelized cost of transmission. For the present study, it is assumed that the energy generation system of the Netherlands will be 100% renewable in 2050, based on the generation portfolios outlined in the studies conducted by Finland's LUT, Schlachtberger et al for Europe, Jacobsen et. al, and Berger et al. These studies provide a better estimate of the levelized cost of energy. The Levelized System Cost of Electricity can be assumed to be €54 – €110 /MWh for the 100% renewable energy generation system of 2050. Calculation of electricity tariffs will be as per Bekhuis' thesis "The role and potential of a hybrid heat pump in an existing Dutch house".

As electricity will be provided to the end user by retail companies, the energy tariff to the consumer will have to include the administrative and other supply costs of the retail companies (retail markup). Thus, the Levelized Cost of Energy will provide an initial estimate of the electricity tariff, the supply tariff charged to the consumer will have to reflect these additional costs. According to CBS Statline, under 'Energy Prices - Natural Gas and Electricity, Average Price for End Users', consumer tariffs in the Netherlands, as charged to households, are comprised of two components – delivery price and network price. [12]

Delivery prices include the fixed and variable costs, Sustainable Energy Production Charge, VAT, energy tax, and energy tax refund. Flexibility and storage costs make up a small portion of present-day tariffs, however, they are likely to increase significantly for a 100% renewable energy system. Network prices involve the compensation for the use and maintenance of the electricity grid, including the cost of installing and maintaining electricity meters. Energy taxes and VAT are subject to government policy and are not included in the electricity tariffs in the present study. The delivery price and the network price together make up the transaction price charged to the end consumer. Different rates are charged based on levels of annual energy consumption per user. [12]

The delivery charges are comprised of fixed and variable tariffs. The variable tariffs are the electricity tariffs charged to the consumer for electricity consumption per unit of energy, based on system marginal cost of the electricity generation system, or levelized cost of electricity generation. The fixed delivery rate and electricity transport rate are charged to the consumer monthly. For the analysis in this study, the variable delivery rate exclusive of VAT and energy taxes will be used to calculate household energy bills. The fixed costs are based on maintenance of the electricity grid and transport costs which are likely to increase in future.

Table 3.2 – Energy Price Data

Year	Variable Delivery Rate (euros/kWh)	APX Spot Prices (euros/kWh)	Difference in price (%)
2018	0.059	0.055	7
2019	0.066	0.042	33

Source – CBS Statlne and energiemarketinformatie.nl

In 2018, the variable delivery rate for electricity was 0.059 euros/kWh, and in 2019 the average price was 0.066 euros/kWh when VAT and other taxes were excluded, according to CBS. The Amsterdam Power Exchange day-ahead prices for the same period was between 0.022 euros/kWh and 0.09 euros/kWh, with approximate average prices of 0.055 euros/kWh in 2018 and 0.042 euros/kWh 2019, according to energiemarketinformatie.nl, [13] which is a surprising trend – prices tend to increase every year. However, only a small part of the total electricity demand is traded on the day-ahead spot market, while the cost figures give an idea of the electricity tariff, actual electricity tariffs through the year may have been higher. From these values, we can say that there is an increase in production cost per unit of electricity when charged to the consumer as electricity retail price (difference between Variable Delivery Rate and APX Spot Price) of between 0.4 cents/kWh to 2.4 cents/kWh (between 7% and 33%).

In order to investigate the effect of electricity price on overall cost, 5 electricity prices have been chosen to represent scenarios with low electricity price and high electricity price for the present study, with electricity production costs of the system (system levelized cost of electricity includes the levelized cost of electricity generation, curtailment, storage and transmission) ranging from 0.054 euros per kWh to 0.110 euros/kWh in the Netherlands in 2050. From the observations of the energy statistics from CBS Statline and the electricity spot prices from APX, the final electricity tariff that the consumer will have to pay will be marked up from these production prices by 0.024 euros/kWh (2.4 cents/kWh). It is necessary to consider this price difference to make the future price scenarios realistic.

As mentioned earlier, the other two components of the electricity tariff are the delivery charges – fixed and variable delivery rate, and the network transmission charges, or the transport rate, which are annual. For the year 2018, the transport rate and fixed delivery rate together amounted to 243 euros/year, according to CBS Statline, under 'Energy Prices – Average Energy Rates for Consumers'. [12] The average electricity consumption per household in the Netherlands in the year 2018 was 2790 kWh per household, according to CBS Statline, under 'Energy Consumption by Sector – Energy Consumption in Private Homes; Housing Types and Regions'. [14] The rate in euros/kWh is 0.087 euros/kWh. This rate is independent of the amount of electricity consumed and charged to the consumer every year. As these fixed costs do not change from one household to another, but are based on the supplier of electricity, (or gas, in this study, hydrogen), which presents more uncertainty, they will be excluded from the present study. The assumed electricity production cost in the present study includes the levelized cost of electricity transmission as well, so this prevents the transmission cost being counted twice.

In CBS Statline, in the page "Natural gas and electricity, average prices of end users", the total price of electricity per kWh for consumers of different consumer classes (households, businesses, etc.) is given to be comprised of two parts – delivery price (fixed costs, variable costs, energy taxes, ODE, sustainable energy production charge) and network price, or distribution costs (fee for the use, maintenance and connection to the electricity grid including the cost of electricity metres and their maintenance). [15] These costs are dependent on the energy supplier as well, and also on the capacity of electricity specified in the contract between supplier and consumer. Since these are also not based directly on energy consumption (all households within the same capacity bracket will pay the same capacity-dependent annual costs to the supplier), these costs are excluded from the electricity tariffs in the present study for the Netherlands in 2050.

Also charged to households annually is the energy tax reduction. The energy tax reduction is set by the government for the year based on the concession that a certain amount of energy consumption is a basic necessity for living. This basic amount of energy is reflected as a reduction in the total annual energy bill per user or household connected to the electricity grid. [16] This amount is determined by government policy, and is the same for all households. The energy tax reduction has also not been considered in the present study. The electricity prices have been presented in the Table 3.3. Five electricity tariffs are chosen based on the literature, all in euros/kWh –

(1) 0.057 (2) 0.068 (3) 0.082 (4) 0.0857 (5) 0.110 – these are inclusive of the levelized cost of electricity generation, levelized cost of curtailment, levelized cost of storage and levelized cost of transmission

Table 3.3 – Future Electricity Tariffs (2050)

Levelized System Cost of Energy of the 100% renewable energy system of 2050 (euros/kWh)	Electricity Retail Markup (euros/kWh)	Electricity Tariff = Levelized System Cost + Retail Markup (euros/kWh)
0.057	0.024	0.081
0.068	0.024	0.092
0.082	0.024	0.106
0.086	0.024	0.110
0.110	0.024	0.134

3.4 Inputs for Future Hydrogen Prices

Studies have been undertaken to determine the feasibility of producing hydrogen in the Netherlands, and other European countries. These studies have been presented as the basis for selecting the hydrogen prices in the present study. Other studies analysing the feasibility of utilising the current gas transport grid for transporting 100% hydrogen, and their results are also discussed. Space heating falls under

"Low Temperature Heat" application. A low temperature heating system is one in which the hot water that leaves the heat generator has a temperature less than or equal to 45°C, even on the day with cold weather conditions that are in place to calculate the maximum heat loss from the space or dwelling. [17]

The main devices that are used for space heating in Netherlands are central heating boilers, with a small number of users of conventional electric heat pumps. Another conventional device is the all-electric resistive heater. Hybrid heat pumps are also being considered for future applications space heating using only renewable energy. In this case the heating is mainly performed with an electric heat pump, for space heating, but the capacity required to meet peak demand for heat during the coldest times is provided by a natural gas boiler. However, the gas could also be hydrogen here. The peak timing usages are mainly for boiling water, which requires a fast response time. These peak usages can be facilitated by using the integrated gas fired boiler.

According to a study "Exploration of Hydrogen Infrastructure" by DNV GL, Netherlands is the 2nd largest producer of hydrogen in Europe, behind Germany, producing 10 billion cubic tons of hydrogen a year. It is produced mainly on-site from natural gas in industrial clusters in Northern Netherlands, Rotterdam and Zeeland. These areas appear to be relatively better suited to be the first areas where hydrogen may play an important role. Hydrogen has a calorific (HHV) value of 39.4 kWh/kg. The energy content of all the hydrogen produced worldwide exceeds the energy consumption of Netherlands 3 times over. [3]

3.4.1 Hydrogen for Heating

The climate targets call for a wide reduction in the use of natural gas, or to combine natural gas with carbon capture and storage. This study excludes the use of carbon capture and storage for analysis. Thus, for deep decarbonisation, a clean fuel alternative needs to be utilised in place of natural gas. The residential heating network in the Netherlands is similar to the in the UK – both are based on natural gas, both have a combination of district heating options and individual gas-fired boiler based central heating for individual households.

From the studies done in the UK, one possible alternative to natural gas is to use hydrogen as an energy carrier. The gas network needed to distribute hydrogen, where distribution of hydrogen is desired, could be very similar to the current natural gas network, requiring few changes. The first, most important modification that the network operators need to regard is the determination of the supplied amount of energy. A second requirement is that suitable end-use devices for burning hydrogen need to be made available, as most devices built for natural gas use will not support the use of hydrogen. Almost none of the existing devices available to end-users are suitable for the use of 100% hydrogen.

The combustion of hydrogen in the existing central-heating boilers may result in flame flashback and damage to the burner. A minimum precaution is that hydrogen give off a recognizable odour, preferably with the aid of a sulfur-free odorant, in the case of a gas leak, same as with gas. Another important factor, especially for indoor applications of hydrogen in households, is the safety regarding the outflow of unwanted gas, such as excavation damage. The security principle (ionization current) in the current apparatus is not applicable to 100% hydrogen. This also applies to most gas cookers. An increased safety risk with cooking appliances is that burning of hydrogen does not produce visible flame. [18]

3.4.2 Hydrogen Production from Electrolysis of Water

Hydrogen can be produced in many ways, as outlined in the study "Outlines of a Hydrogen Roadmap" by J. Gigler of TKI Nieuw Gas. The historic production of hydrogen has been based on Methane Reforming, which has high carbon dioxide emissions associated with the process. However, if biogas is used, rather than natural gas, the associated carbon dioxide emissions come from the current carbon cycle and do not inject additional carbon dioxide the way fossil fuels do – the associated emissions are zero. [19]

The other method of production is through electrolysis of water using either curtailed grid electricity, or using dedicated hydrogen electrolysis plants with on-site electricity generation. Electrolysis can only be valid as a decarbonisation option if the electricity is produced with zero emissions. Rapid developments in solar photovoltaic technology and in wind energy generation would be needed to facilitate this transition.

Alkaline Electrolysis and Proton Exchange Membrane electrolysis are the most well-known, with alkaline electrolysis being the most technologically mature option. In the report by Gigler, the figures for investment costs of alkaline electrolysers were retrieved from Lymperopoulos, N. (2017), FCH JU presentation at the International Conference on Electrolysis, Copenhagen, 12 June 2017. The figures for future investment costs by 2030 were retrieved by Gigler from Bertuccioli L., et al., (2014) with E4tech Sàrl with Element Energy Ltd for the Fuel Cells and Hydrogen Joint Undertaking, February 2014. The rest of the figures are by Gigler. [20]

Table 3.4 - Alkaline Electrolysis vs. PEM Electrolysis

	Alkaline Electrolysis	**Proton Exchange Membrane Electrolysis**
Scale	1MW – 5MW	1MW – 5MW
Investment costs	€1,000 per kW	€1,400 per kW
Investment cost estimate by 2030	€370 - €800 per kW	€250 - €1270 per kW, (€760 per kW median cost estimate)
Expected System Efficiency by 2030 (based on LHV)	67%	>70%
Expected production costs by 2030	<€2 - <€3 per kg (on-site production)	<€2 - <€3 per kg (on-site production)

According to the report "Outlines of a Hydrogen Roadmap", with the assumption that large units with a capacity of 10-100 MW (which produce 4-40 tonnes of hydrogen a day) will also have become available by 2030, and will be centrally positioned, the production costs could potentially drop below €3 per kg and possibly even below €2 per kg. Considering that natural gas and CO_2 prices are likely to increase and production via steam methane reforming will likely need to be combined with Carbon Capture and Storage technologies as decarbonisation efforts intensify, electrolysis could likely become economically competitive with central production by natural gas reforming.

According to TNO, (2019) [21] MW scale electrolysers exist in Netherlands, but the scale needs to be upped a thousand fold to reach GW scale, which it predicts by 2025 to 2030. This kickoff article by the Institute of Sustainable Process Technology (ISPT, 2019) [22] also mentions the same thing - present electrolysers are a few MW in capacity.

The future prices of these methods of producing hydrogen would also depend on future electricity prices. Determining these prices involves a high degree of uncertainty. However, electrolysis is able to compete with bulk production via steam reforming of natural gas more readily for small-scale applications, as of 2025. In order for electrolysis to become the new standard for hydrogen production, efforts will need to be dedicated to the development and up-scaling of this technology. [20]

3.4.3 Studies for Future Hydrogen Production Costs

In the study "Economics of Converting Renewable Power to Hydrogen" by Glenk and Reichelstein, a general energy system was modelled as an electricity generator coupled with an electrolysis unit (renewable energy source coupled to an electrolyser) for the year 2050. The model was applied to wind parks in Germany and Texas, to identify the profitability of operating such plants. The study notes that in places where renewable energy generation methods are competitive with conventional generation (as is the case with wind energy in Germany), the price per kilogram of hydrogen sold is lower than in places where renewable sources of energy cannot compete with conventional sources as yet (as is the case in Texas). The study notes that with the decline in price of wind turbines, improved capacity factors, and the decline in electrolyser prices could improve the competitiveness of hydrogen. The break-even price for hydrogen in Germany was found to be around 0.3 €/m^3 (85.56€/MWh). [23]

A study conducted by Navigant in 2019, "Gas for Climate - The Optimal Role for Gas in a Net-Zero Emissions Energy System" discussed pathways for replacing natural gas with alternative clean fuels to fully decarbonise the energy system of the entire European Union. The study highlights hydrogen as a fuel with high potential to facilitate deep decarbonisation across all sectors of human activity. The Navigant study notes that in order to produce green hydrogen, that is, hydrogen produced via electrolysis using only solar photovoltaic or wind power, production could be done by dedicated hydrogen power plants that use their own photovoltaic and wind turbine generators, or by utilising curtailed grid electricity. The green hydrogen production cost using dedicated offshore wind power from the North Sea was found to be between 48€/MWh and 61€/MWh by the year 2050, with feedstock electricity cost taken as 30 – 40 euros/MWh. Using curtailed grid electricity, the price varied between 17€/MWh and 71€/MWh by 2050. [24]

According to the report "Path to Hydrogen Competitiveness" (2020), hydrogen production costs could become about 2.1 euros (2.5 dollars)/Kg by 2030 in Europe. With electrolysers costing 500 dollars/kW, electricity price at 30 dollars/MWh and a 30% load factor, hydrogen production costs are found to be 1.4 dollar to 2.8 dollar/Kg (1.18 euro – 2.36 euro/Kg). [25]

According to "the Green Hydrogen Economy in the Northern Netherlands", large scale green hydrogen, centred around Northern Netherlands, could create hydrogen production costs of 2 – 3 euro/Kg by 2030, given that the electricity input price is 20 – 30 euros/MWh. (hydrogen production of 2.3 euros/Kg with electricity at 25 euros/MWh, via electrolysis). Northern Netherlands has very good access to wind energy resources and the electrolyser can be run at very high load factors, advantageous for centralised production. [26]

In March, 2020, BloombergNEF published a study wherein it was estimated that green hydrogen production costs of as low as $1/kg of hydrogen was achievable in parts of the world like China and Western Europe by 2050. [27] This translates to a production cost of €26.72/MWh of hydrogen (HHV) – half the value given by Navigant and much more optimistic than the previous studies detailed earlier. The levelized cost of various hydrogen storage technologies are also given in the study. The study mentions that green hydrogen production costs could reach $0.7 - $1.6/Kg in most parts of the world by the year 2050.

According to "Hydrogen: A Renewable Energy Perspective" (IRENA) predicts hydrogen production costs of $1.5 - $2/Kg by 2050, provided average solar PV and wind availability. For the best case, the prices are $1 - $1.2/Kg. The study also notes the benefit of transmitting hydrogen produced in distant locations with high renewable energy generation potential, and transported to areas of high demand. These could bring hydrogen costs down in areas that have lower renewable energy generation resources available, which were also highlighted in "Path to Hydrogen Competitiveness" and the BloombergNEF report. [28]

According to "Green Hydrogen for a European Green Deal A 2x40 GW Initiative", the north and south of Europe have excellent renewable energy generation potentials. The main centres of hydrogen demand in Europe will be at a distance from these generation sites. The study suggests generating hydrogen at the renewable energy generation site and transporting the hydrogen via pipelines, to the end-user sites. North Africa has better wind and solar generation capabilities than the south of Europe and. Electricity transmission by cable is 10 – 20 more expensive than transporting hydrogen by pipeline. Hydrogen storage in salt caverns is a factor of 100 less expensive than storage through batteries. Transporting hydrogen from North Africa to Europe would cost 0.2 euros/Kg of hydrogen, in 2050, the study found, for an integrated Europe-North Africa-Ukraine market. Electricity prices determine 60 – 80% of the hydrogen production cost. [29]

Table 3.5 – Summary of Literature

Study	Hydrogen Price
Glenk and Reichelstein (for 2050)	At least 85.56 euros/MWh
Navigant (for 2050, with dedicated wind generation for hydrogen)	48 – 61 euros/MWh (hydrogen production cost)
Path to Hydrogen Competitiveness (for 2030)	1.18 – 2.36 euros/Kg (29.5 - 59 euros/MWh)
The Green Hydrogen Economy in the Northern Netherlands (for 2030)	2 - 3 euros/Kg (50 – 75 euros/MWh)
BloombergNEF (for 2050)	0.7 – 1.6 euros/Kg (17.5 – 40 euros/MWh)
IRENA (average case for 2050)	1.5 – 2 dollars/Kg (32 – 42.5 euros/MWh)
CE (for 2030)	1.72 euros/Kg (43 euros/MWh)

CE (2018) analysed the chain costs for producing hydrogen from offshore wind turbine installations off the North Sea in 2030. The electricity input cost for production was 48 euros/MWh (including offshore grid costs) and led to green hydrogen supply chain costs of 2.92 euros/Kg with an uncertainty of 25% either way. The marginal cost of green hydrogen from North Sea wind turbines was 1.72 euros/Kg (25% uncertainty either way). Figures to 2050 are not available. [30]

3.5 Setting Future Hydrogen Tariffs

There is a high degree of uncertainty regarding the production costs of hydrogen. Costs are expected to fall drastically from today's levels as long as a hydrogen economy is built to ensure it. For the purpose of this study, it is assumed that green hydrogen production and all hydrogen boilers and hybrid devices are mature technologies, with comparable costs to the current gas infrastructure of Netherlands in the year 2050. According to the DNV GL study "Verkenning waterstofinfrastructuur", the northern part of the Netherlands is particularly well suited to developing a hydrogen economy.

The hydrogen required for the hydrogen and hybrid scenarios in the present study will be produced via electrolysis of water, using renewable electricity. Hydrogen imports are not considered – the hydrogen is assumed to be produced entirely within the Netherlands. It is further assumed that hydrogen will be transported to households using the existing natural gas pipelines of the Netherlands, after the high pressure network has been modified to accommodate 100% hydrogen. The levelized cost of hydrogen production will give an indication of the hydrogen retail tariffs. The final retail tariffs charged to the consumer are higher than these production costs, to account for the network and distribution costs, with the same reasoning as electricity tariffs.

The study undertaken by Navigant was a system-wide study for the whole of the EU. Energy generation was 100% renewable, based on a mixture of renewable energy generation technologies, energy storage, grid strengthening technologies and national grid interconnections with neighbouring countries. In the study, the calculated green hydrogen production costs for the year 2050 were determined through the interactions of these various agents. Using dedicated wind energy generation in the North Sea, the price varied between €48/MWh and €61/MWh by 2050 (lower load factors lead to higher tariffs). In addition, the report by TKI Nieuw Gas indicates that hydrogen production costs could potentially fall to between €50 and €75/MWh by 2050. Studies in countries such as Germany indicated hydrogen production costs to be €85/MWh. More recent studies indicate a hydrogen production cost of 15 euros/MWh – 75 euros/MWh will be possible in many parts of the world.

For the present study, a renewable energy generation system is assumed to provide energy for the Netherlands by the year 2050, similar to the studies presented before. Electricity prices are assumed to be 80% of the production cost of hydrogen from electrolysis. Hydrogen is produced by dedicated hydrogen production RES in the form of offshore wind turbines. Cost estimates for 2030 are taken as figures for 2050 for the Netherlands could not be found, from the report "the Green Hydrogen Economy in the Northern Netherlands" (offshore wind cost of 20 – 30 euros/MWh). The Navigant study from 2019 indicates electricity tariffs of 30 – 40 euros/MWh (including the grid costs for the offshore grid) as appropriate as feedstock price for hydrogen electrolysis. The hydrogen production costs calculated in the study indicated that the electricity cost was 60 – 70% of the production costs for hydrogen.

Cost of transmission from Northern Netherlands to the rest of the country will be taken as 0.2 euros/Kg of hydrogen, based on the "2 x 40 GW" study. Wind energy feedstock input cost is assumed between 20 – 40 euros/MWh including offshore grid costs. Electricity prices are assumed to equal 70% of the production cost of hydrogen (60% – 80% of production cost determined by the electricity price, as taken from the "2 x 40 GW study"). As there are no similar figures or price reduction projections in the study for the remaining 30% of the cost, the hydrogen production cost is assumed to be obtained by simply being 1.43 times higher than the electricity feedstock tariff. This brings the hydrogen production costs to 28.57 – 57.14 euros/MWh of hydrogen. Pipeline transport from Northern Netherlands (transmission) will add 0.2 euros/Kg, or 5.1 euros/MWh. Two other tariff inputs come from the literature, both for the year 2050. From the IRENA report, the hydrogen production cost of 32 euros/MWh in 2050 was selected as it is consistent with having a wind energy feedstock price of 22.37 euros/MWh and taking electricity tariffs as 70% of hydrogen production cost. From the Navigant study, the hydrogen production cost of 61 euros/MWh was selected as it was the highest cost for 2050 that was consistent with the current assumptions in the present study. These studies were chosen as they showed costs up to the year 2050.

Table 3.6 – Hydrogen Production and Transmission Costs (2050)

Wind Energy Feedstock Price (euros/MWh)	Hydrogen Production Cost (euros/MWh)	Hydrogen Pipeline Transport Cost (euros/MWh)	Hydrogen Production + Transmission Cost (euros/MWh)
20	28.57	5.1	33.67
N/A (IRENA study)	32	5.1	37.5
30	42.85	5.1	47.95
40	57.14	5.1	62.24
Navigant study	61	5.1	66.1

Similar to the electricity tariffs seen earlier, natural gas tariffs in the Netherlands are comprised of two components, namely, the delivery cost and the network cost, according to CBS Statline, under 'Natural Gas and Electricity – Average Prices of End-Users'. [14] Delivery prices include the fixed and variable costs, Sustainable Energy Storage Charge, VAT, energy tax, and energy tax refund. Network prices involve the compensation for the use and maintenance of the gas grid, including the cost of installing and maintaining gas meters. Energy taxes and VAT are subject to government policy and are not included in the hydrogen tariffs in the present study.

The delivery price and the network price together make up the transaction price charged to the end consumer. Different rates are charged based on levels of annual energy consumption per user. The delivery charges are comprised of fixed and variable tariffs. The variable tariffs are the gas tariffs charged to the consumer for gas consumption per unit of energy, based on system marginal cost. The fixed delivery rate and electricity transport rate are charged to the consumer annually. For the analysis in this study, the variable delivery rate exclusive of VAT and energy taxes will be used to calculate household energy bills.

For the year 2018, according to CBS Statline, under 'Energy Prices – Average Energy Rates for Consumers', the transport rate was 148 euros/year and the fixed delivery rate was 46 euros/year, exclusive of VAT and taxes. These are charged independent of the amount of gas consumed and are unlikely to change much by 2050. Under 'Energy Consumption by Sector – Energy Consumption of Private Homes; Housing Type and Region' in CBS Statline, the average household consumption of gas in the Netherlands in 2018 was 1270 m^3 per household. The energy equivalent of this is 14140 kWh with respect to HHV of gas. Thus, the transport rate in euros/kWh for gas is 0.01 euros/kWh, the fixed delivery rate is 0.3 cents/kWh. These costs are fixed in the same way as the fixed costs for electricity tariffs – they are charged independent of the amount of gas consumed, so will not be considered in the present study.

Similar to the electricity tariffs, there is also a retail cost markup between production and retail of gas. According to CBS Statline, the average natural gas tariff charged to consumers was €0.0281/kWh in 2018, and €0.029/kWh in 2019. The ENDEX Dutch Gas prices averaged approximately €0.019/kWh in 2018, and 0.017€/kWh in 2019, according to energiemarketinformatie.nl. [15] Similar to electricity tariffs, the gas tariffs are marked up by 0.9 to 1.2 cents/kWh (33% to 41%). The hydrogen tariff charged to the consumer in 2050 will also have to be marked up similarly in the present study, to account for network and distribution costs. The retail markup chosen for this study is 1.2 cents/kWh based on the sources mentioned.

Table 3.7 – Gas Price Data

Year	Variable Delivery Rate (euros/kWh)	APX Spot Prices (euros/kWh)	Difference in price (%)
2018	0.028	0.019	33
2019	0.029	0.017	41

Source – CBS Statline and energiemarketinfornatie.nl

The final hydrogen tariffs including the retail markup is shown in Table 3.8.

Table 3.8 – Future Hydrogen Tariffs (2050)

Hydrogen Production + Transmission Cost (euros/kWh)	Hydrogen Retail Markup (euros/kWh)	Hydrogen Tariffs (euros/kWh)
0.034	0.012	0.046
0.038	0.012	0.050
0.048	0.012	0.060
0.062	0.012	0.074
0.066	0.012	0.078

3.6 Space Heating and Domestic Hot Water (DHW) Demand

The space heating demand in 2050 will be met by using all-electric air or ground source heat pumps in the electricity pathway. Demand in the hydrogen pathway will be met using end-use hydrogen-only boilers. The hybrid pathway will see demand being met using a combination of all-electric heat pumps and hydrogen boilers in a device called a hybrid heat pump. First, the annual space heating and domestic hot water demand per household needs to be determined. Then, using the investment costs, installation costs, home renovation costs and energy costs of each decarbonisation technology per household, the cost of each decarbonisation pathway can be calculated.

3.6.1 Determining Annual Space Heating Demand

In order to determine the cost of each decarbonisation pathway, the annual space heating demand per household must first be determined. Studies have been done to determine the method by which space heating demand can be calculated. In the report "Average EU building heat load for HVAC equipment" prepared by Rene Kemna for the European Commission in 2014, the average heat load of the built environment was calculated for the entire European Union. [31] Heat demand was modelled as the sum of the transmission and ventilation losses (which represent heat outflow from the space under consideration) minus the solar and internal gains (which represent heat inflow into the space under consideration).

Transmission losses are conductive heat losses through building surfaces such as windows, doors, walls and roofs. Ventilation losses are the heat flow through open windows and ventilation units, and infiltration of air through openings in the shell of the dwelling. Solar gains are the energy gains from solar energy (sunlight) input through windows. Internal gains come from the heat produced by people and non-heating electrical appliances such as lightbulbs, computer and television screens and central processing units of computers. These parameters are used to calculate the heat demand for any type of building. [31]

The indoor temperature during the heating season is crucial in calculating the annual space heating demand of a dwelling. According to Kemna, to calculate annual space heating demand of the built environment, at the national level, it is common practice to assume that the average indoor temperature for indoor comfort in Western Europe is 18°C for the heating season (period of the year over which heat needs to be provided for the residential sector). This temperature is a surface weighted average based on 20 – 21°C for living rooms, 16 – 17°C for bedrooms, 24°C for bathrooms, and 18°C for kitchens. For calculating the space heating demand on national or international scopes, it is not useful to explicitly calculate the solar and internal gains, according to Kemna. Instead, the solar and internal gains are considered implicitly by reducing the indoor temperature required for comfort. After correcting for solar gains and internal gains, the reference temperature drops to 15°C. [31]

The aim of the present study is to calculate the annual cost of each decarbonisation scenario for the Netherlands as a whole. The study does not address improvements to building elements such as windows and walls, it is not useful to include the solar and internal gains explicitly in modelling. The annual energy cost to the consumer will be a function of the annual heat demand, and the annual energy tariffs. The formula used by Kemna in the study "Average EU building heat load for HVAC equipment" takes into account the average indoor and outdoor temperatures, the length of the heating season, and external dimensions of the dwelling. [17] The present study addresses only the changes to the energy demand side. Thus, the annual space heating demand per dwelling has been calculated according to the formula in the study by Kemna. The formula is –

$$Q_{building} = 0.001 * \Delta T * t_{heating} * [(S * U) + V * q(1 - rec) * c_{air}] \ kWh \qquad (xi)$$

where

- $Q_{building}$ is annual building space heating demand [kWh/a],
- ΔT is indoor-outdoor temperature difference corrected for solar and internal gains [K] = $T_{ambient} - 15°C$
- $t_{heating}$ is heating season hours [h], = 5524 hours
- S is heated shell surface area, built from areas for exterior walls, windows, floor, roof [m²],
- U is the average thermal transmission coefficient derived from shell surface area weighted specific U-values [W/m².K],
- V is heated building volume [m³],
- q is hourly air exchange [m³.h-1/m³],
- rec is the fraction of heat recovered from outgoing air [-],
- c_{air} is specific heat capacity air [0.343 Wh/m³.K],

- is the conversion factor from Wh to kWh.

For this study, the reference of 15°C is used to account for the effects of solar and internal gains. In addition, the KNMI temperature projections (according to the KNMI '14 Climate Scenarios Brochure) for the year 2050 estimate that average temperatures on Earth could be increased between 1°C to 2.5°C throughout the year. [32] Temperature data from TUDelft PV Portal [33] have been increased by 2.1°C, according to the WH 2°C scenario, representing the highest average increase in temperatures, to obtain the temperature conditions for the purpose of this study. From the data on hourly ambient temperatures in Netherlands, (obtained from TUDelft PV Portal) the number of hours in the year where the external temperature is less than 15°C is 5524 hours. The average ΔT was found to be 5.57°C for the heating season.

3.6.2 Thermal Mass and Urban Heat Island

In addition to the required indoor temperature, the average temperature difference between the indoor space and the outdoors over the heating season needs to be determined. In a study by Karmen Van Dyke, titled 'Green Walls in the Urban Netherlands', it is mentioned that in the Netherlands, the heating season is generally taken to be seven months, the calendar period between 1 October and 1 May. [34] This heating season length was taken from the Kemna study. In addition, the heating season was also taken to be seven months in the Netherlands in Dasa Majcen's study titled "Predicting energy consumption and savings in the housing stock - A performance gap analysis in the Netherlands". [35]

The study by Kemna notes that the standard method of calculating heating demand by heating degree days (number of days in the year in which the average outdoor temperature is lower than the reference indoor temperature value) will result in an overestimation of the average heating demand. The heating season is related to the outdoor temperature because the heating season length (in hours) can be calculated by calculating the number of hours in the year where the outdoor temperature is lower than 15°C. Hourly outdoor temperatures during the heating season can be obtained from meteorological data from meteorological stations, or from organisations like KNMI.

The calculation for heating hours does not include the effect of thermal mass of the building, which maintains a relatively more constant heating load as the building materials absorb and store heat from hour to hour. The effect of this thermal mass will result in the further rise of the average outdoor temperature during the heating season. Urban areas are a dense collection of various infrastructure that creates heat. Buildings also shield each other from wind. The average outdoor temperatures in urban areas is thus significantly larger than in rural areas, known as urban heat island effect. Urban heat island formation in urban areas leads to the rise in temperatures in urban areas, compared to meteorological measurements at met stations, which are often located in sparsely populated areas and may not reflect the true temperature in built up areas. Thus, to correct for heat island effects, the average temperature during the heating season has to be estimated as higher than the calculated average. [31]

The effect of urban heat islands and the thermal mass of the building has been taken as a temperature rise in this study, the average temperature of the heating season in this study was found to be 6.5°C, using a similar increase as outlined in the report "Average EU building heat load for HVAC equipment". This value, coincidentally, also corresponds with the EU-wide average temperature of the heating season, found in the report to be 6.5°C. Therefore, in this study, the effects of solar gains, building thermal mass, urban heat island effects and internal gains have been included implicitly in the values of ΔT and $t_{heating}$ and are not calculated separately.

3.6.3 Building Volumes and Surface Areas

Dwellings gain or lose heat through surfaces such as walls, floors, roofs and windows. In the Netherlands, houses are divided into detached houses, semi-detached houses, terraced houses and flats. Flats can be further divided into high rise and low rise flats. Dwellings in the study "Average EU building heat load for HVAC equipment" are similarly divided. The study takes a top-down approach to assuming the dwelling parameters.

In order to calculate the space heating load for buildings of any type, the volume to be heated (total volume of the dwelling/room) needs to be determined, along with the dwelling shell surface area. In order to carry out calculations for the space heating demand across the EU, assumptions about building dimensions were made, in the Kemna study, after extensive data analysis from several sources, including census surveys, land registry examination, urban planning guidelines, architectural guidelines for floor area and building volume, architect data for reference buildings, monetary and real estate data, data from national statistics offices and Ecodesign preparatory studies. [31]

Table 3.9 - Assumptions for types of homes (2050)

Type of home	Surface Area/Volume	Shell Surface Area (m^2)	Shell Volume (m^3)	Building dimensions (m)	Heated Floor Area per dwelling (m^2)
Terraced	0.55	3712 in total for 15 dwellings	6750	90x7.5x7.5	128
Flat - Low Rise	0.31	3002 in total for 25 dwellings	9660	12x35x23 - 4 floors	67.5
Flat - High Rise	0.24	9648 in total for 130 dwellings	40320	12x80x42 - 13 floors	96
Detached	0.85	340	400	8x10x5	158
Semi-Detached	0.61	495 in total for 2 dwellings	810	12x9x7.5	140

Source - "Average EU building heat load for HVAC equipment" – Kemna, and CBS Statline

In the report by Kemna, it is mentioned that extensive records of housing data, dwelling floor area, dimensions of the walls and exact heated floor area do not exist for the majority of building stock in the EU, including the Netherlands. [31] The present study aims to make a first order estimation of the annual cost per scenario, it is not especially useful, for the scope of the present study, to include the variations in building dimensions for every dwelling. A top-down approach that takes into account the representative types of dwellings in the Netherlands is more useful to adopt.

Dwellings are divided into five types in the present study – detached houses, semi-detached houses, terraced houses, and low and high-rise flats. All dwellings of the same type are assumed to have the same floor area and surface area to volume ratio. The assumptions for terraced houses and low and high-rise flats from the study undertaken by Kemna have been used as shown in Table 3.9. The value of ventilation air exchange ($q.(1 - rec)$) has been taken from this report as well, which was found by Kemna to be 0.68 for residential building stock. [31]

Ventilation rates were calculated for the EU as a whole. Sources used by the author Rene Kemna, of Van Holsteijn and Kemna (B.V.) or VHK, were from Ecofys 2010, for the overall volume of air ventilation over the whole built environment of the EU. These values were used to find the overall air exchange rate q. Using additional data on the division of the built environment based on type of building (residential or non-residential), the overall air exchange rate q for the residential sector was determined at 0.72. From the overall ventilation data, the rate of heat recovery was determined as a percentage of total ventilation. The heat recovery rate for the entire EU residential sector was found to be 5%. [31]

$$0.72 * (1 - 0.05) = 0.68$$

Only detached dwellings are taken as single-family homes in this study, all the other types of dwellings have been taken as multi-family buildings, according to the assumption by Kemna, that semi-detached houses would be considered as two dwellings to a building. CBS Statline gives the average area per dwelling, the average floor area of single family houses built from 1850 to 2019 was $158m^2$ [36]. The average area for semi-detached homes was assumed to be $140m^2$, as semi-detached homes are intermediate in size to detached houses and terraced houses, according to CBS statline.

3.6.4 Building Insulation

The level of insulation in a dwelling will also influence the space heating demand – better insulation means a lower space heating demand. Insulation levels are denoted by a quantity known as 'U-value'. It is a measure of the rate at which the space or dwelling loses heat to ambient air. Lower the U-values mean better insulation. In the Netherlands, household insulation grades go from grade G, with the poorest insulation, to grade A++, having the best insulation.

In the thesis "Predicting energy consumption and savings in the housing stock - A performance gap analysis in the Netherlands" by Dasa Majcen, default building U values of houses with different energy labels in the Netherlands were used in order to calculate space heating demand using the EPA method, for building insulation class A to G. The default values were based on an analysis carried out on the energy label database of AgentschapNL, the agency of the Dutch Ministry of the Interior and Kingdom Relations that manages the official registration of the energy labels consisting of all dwelling labels registered in 2010 (342,194 cases). The study notes that using their method, the theoretical energy use estimations were underestimated for dwellings with insulation class A and B, while for insulation classes C to G, the energy consumption was overestimated. [35] The U values corresponding to insulation grade have been presented in Table 3.10.

Table 3.10 - U value assumptions based on energy label (2050)

Energy Label	U value (W/m^2K)
A	0.2
B	0.36
C	0.50
D	0.64
E	1.6
F	2.0
G	2.4

Source -"Predicting energy consumption and savings in the housing stock -A performance gap analysis in the Netherlands" - Dasa Majcen

Standard U values per insulation label do not exist, U values are calculated on the basis of individual dwellings, by calculating the heat resistivities of the walls, windows, floors and ceilings of individual dwellings. As stated earlier, such detailed information on dwellings in the Netherlands does not exist or is not readily available. In addition, reference U-values are also not given in relation to the insulation label grade.

The present study aims to make a comparison on the basis of household insulation, in order to include the effect of building insulation on the coefficient of performance of electrical and hybrid heat pumps, and also to study the effect of household renovations on the overall annual cost per scenario. The annual space heating demand per dwelling depends directly on the average U value of the dwelling. For these reasons, for the present study, the reference U values have been taken from the U values calculated in the thesis “Predicting energy consumption and savings in the housing stock -A performance gap analysis in the Netherlands” by Dasa Majcen. [35]

3.6.5 Determining Hot water Demand

Table 3.11 – People per Dwelling for Different Size Dwellings

Average Floor Area (square metres)/Dwelling	People/Dwelling
50 - 75	2.2
75 – 100	2.8
100 - 150	3
>150	3.2

Source -“Predicting energy consumption and savings in the housing stock -A performance gap analysis in the Netherlands” - Dasa Majcen

In the study by Dasa Majcen, average number of occupants per dwelling size were given, based on EPA Calculations for household energy consumption certifications. From the space heating assumptions for the present study, we assume 2.2 people per low rise flat, 2.8 people per high rise flat, 3 people per terraced and semi-detached house, and 3.2 people per detached house. In Bekhuis’ thesis, it was assumed that domestic hot water requirement was 40.29l per day per person. It is also assumed that the water has to be heated to 60°C. This gives us the daily hot water requirement in 2050 per household in the present study as -

- Low rise flat – 88.63l/day (2.2 * 40.29)
- High rise flat – 112.82l/day (2.8 * 40.29)
- Terraced, Semi-detached houses – 128.87l/day (3 * 40.29)
- Detached houses – 128.93l/day (3.2 * 40.29)

This demand for hot water is assumed to be constant each day. The annual hot water demand in the present study is calculated over the full year, not just over the heating season, unlike the space heating demand, to reflect the relatively constant demand for hot water throughout the year. Assuming water has to be heated to 60 degrees Celsius from 15 degrees Celsius [37] –

$$energy\ required\ per\ house\ per\ year\ = \frac{daily\ hot\ water\ demand\ (l/day) * number\ of\ days\ in\ the\ year\ (days) * specific\ heat\ of\ water\ (kWh/KgK) * (60-15)}{Heat\ losses\ through\ pipes\ and\ tank\ walls}$$

Heat losses through pipes and tank walls taken as 0.9 by default in [37]. Using the formula above, we get annual hot water requirement in kWh/year as shown in Table 3.12.

Table 3.12 – Annual Hot Water Demand per Dwelling in 2050

Type of Dwelling	Annual Hot Water Demand (kWh/year)
Low-rise Flat	1872
High-rise Flat	2394
Terraced House	2734
Semi-detached House	2734
Detached House	2738

3.7 Annuity Payment Formula

Investment costs have been converted to annual costs by annuitizing the investments over the lifetime of the device (in the case of investment costs for each decarbonisation technology) or over the lifetime of building insulation (in the case of annuitizing the investments required to improve household insulation levels). The annuity payment formula is given by [44] -

$$P = \frac{r.(PV)}{(1-(1+r)^{-n})}$$

Where

- P = Payment
- r = rate per period
- PV = Present Value
- n = Number of Periods

Rate per period (annual rate) has been taken as 7% in the present study, based on various literature source. Under 'Chapter 7 - Discussion', annual costs are calculated with an annual rate of 4%, a lowered discount rate, in order to see the effect of discount rate on annual costs per pathway.

3.8 Calculating Cost of Reinforcing Household Connection and Disconnecting gas Connection

According to Bekhuis, current houses in the Netherlands have a 1 X 35A electricity connection. Installing heat pumps will also require each household to strengthen the grid connection to 3 X 25A. The study found that under the electricity tariffs used, the fixed (standing) charges did not change when changing the connection to 3 X 25A. The study also calculated the cost of reinforcing the household grid connection as a one-off fee of 200.04 euros per household. Annuitizing over the lifetime of the heat pump, (15 years) we get, by the annuity formula, 21.95 euros/house/year. The cost of disconnecting from the gas grid when using all-electric heat pumps was also calculated as a one-off fee of 567.77 euros per household, annuitized over the lifetime of the device (15 years), we get, by the annuity formula, 62.34 euros/house/year.

3.9 Decarbonisation Technologies, Performance and Costs

Three decarbonisation technologies have been investigated for the present study. Each decarbonisation technology has various cost components which will determine the investment cost per household. In addition, technologies like ground source heat pumps will have significant installation costs. Hydrogen boilers would be cheaper to install, and fuel costs are likely to be the main annual cost to the household. Each technology has varying maintenance costs and lifetimes. Finally, installation of heat pumps (electric, and hybrid) will also need to be accompanied by improvements in home insulation, in order to maximise the coefficient of performance, at further cost to the household.

3.9.1 All-Electric Heat Pumps

All-electric heat pumps are the second alternative method of space heating, for decarbonisation. All-electric heat pumps can be used for heating domestic hot water and also for space heating of air. They are generally better suited when coupled with energy efficiency and energy savings measures, these are implemented in new buildings (according to Dutch policy, for all buildings from 2020 onwards). Therefore, this option may show best results when used in areas with a lot of upcoming construction planned.

The efficiency of heat pumps is denoted by a quantity called Coefficient of Performance (COP). The COP does not indicate the performance across seasons, when the ambient temperature varies rapidly. To account for this, the performance can be further analysed using the Seasonal Performance Factor. [38] There are three types of heat pumps, depending on whether the heat source is the ambient air (air source) or the ground (ground source). Ground source heat pumps are further divided into ground source horizontal heat pumps, and ground source vertical heat pumps. Ground source vertical heat pumps are also known as heat cold storage. The performance of heat pumps will depend on the difference in temperature between the heat source (air or ground) and the space to be heated. [39]

According to “A Review of Domestic Heat Pumps”, heat pumps are generally undersized with respect to the peak electricity demand to increase their utilisation and reduce capital costs. The sizing of the heat pump is key to maximising efficiency. The cost/kW of a heat pump system depends strongly on the capacity, it goes down drastically with increasing capacity. There is also a trade-off between the up-front cost of buying the heat pump, and the running costs, as the more expensive options operate at higher efficiency and those lower running costs. [38]

A technical factsheet by Robin Niessink for air source heat pumps, published by TNO in 2019, states that, according to Milieucentraal (2018), heat pumps provide hot water demand by heating the water to 35°C - 55°C. Once a week, the water is heated by an electric heater (immersion coil resistive heating) to 60°C - 70°C to prevent legionella contamination. The factsheet also states that according to CE (2018), heat pumps need to be combined with low-temperature heating system, needing high quality of household insulation. The minimum energy label recommended by CE, for installing a heat pump, is label C. Low temperature heating systems are underfloor heating or low temperature radiators. In a similar factsheet by Niessink, for ground source heat pumps, the same was found to be true – ground source heat pumps require households of insulation label C or higher, and low temperature heating systems, to maximise performance. [40] [41] Bekhuis mentions the investment cost of low temperature radiators to be between 1540 euros and 1950 euros including installation costs. Also assumed by Bekhuis, was a cost reduction factor of 0.8 for low temperature radiators.

Table 3.13 – Comparison of all-electric heat pumps (from ‘A Review of Domestic Heat Pumps’)

	Air Source Heat Pumps	**Ground Source Horizontal Heat Pumps**	**Ground Source Vertical Heat Pumps**
Expense	Cheapest	Moderate	Most expensive
Drilling Required	none	none	Boreholes between 100 – 150m deep
Area Served	Small	Small	Large [39]
Performance (SPF) Worldwide trials [38]	3 – 3.5	3.3 – 4.2	3.3 – 4.2
Performance (SPF) Energy Saving Trust	1.5 – 2	2 – 2.8	2 – 2.8
Performance (SPF) Fraunhofer Institute	2.6 – 2.9	3.3 – 3.9	3.3 – 3.9

Source - ‘A Review of Domestic Heat Pumps’

The study ‘A Review of Domestic Heat Pumps’ listed the costs separately as capital costs, installation costs and running costs. Heat pumps differ more on the basis of installation costs. On this basis, ground source heat pumps are up to twice as expensive to buy and install as air source heat pumps. Heat pumps have lower running costs than condensing boilers, they also have lower safety regulations and provide greater savings to the end user by also having lower maintenance costs than condensing boilers. They are also more reliable than condensing boilers, according to ‘A Review of Domestic Heat Pumps’. [38] The study notes that with zero risk of gas leakages, the heat pumps need to be serviced every three to five years. The compressor is the main component of the heat pump, with the highest cost and greatest operational complexity. The compressor generally has a lifetime of 15 – 25 years, as mentioned in the report. The mean time between failures was stated to be between 20 and 40 years for small scale ground source heat pump systems, with 1.7% of all compressors requiring annual replacement. [38] These are given in Table 3.13.

According to the technical factsheet on air source heat pumps (Niessink), when assuming a 6kWth air source heat pump, ETRI (2014) indicated the COP of air source heat pumps to be 3.5 by 2050. Startmotor (2018) indicated space heating COP to be 5.25 and domestic hot water COP to be 3 by 2030, no figures after 2030 available. CE (2018) indicated the space heating COP to be 3.5 – 4.5 and domestic hot water COP to be between 2 and 2.6. According to the NTAA performance measurement method, the mean COP for air source heat pumps for space heating is 3.15. [40]

In Niessink's factsheet for ground source heat pumps, a 10kWth ground source heat pump was assumed. ETRI (2014) indicated COP of ground source heat pumps to reach 4 by 2050. Startmotor (2018) indicated space heating COP to be 6 and domestic hot water COP to be 3.3 by 2030, no figures after 2030 available. CE (2018) indicated the space heating COP to be 4.5 – 5.5 and domestic hot water COP to be between 2.75 and 3.75. According to the NTAA performance measurement method, the mean COP for ground source heat pumps for space heating is 4.3. [41]

According to the air source heat pump factsheet, the Nationaal Warmtepomp Trendrapport (2018) estimated the total investment cost, including installation, of air source heat pumps to be between 5000 and 10000 euros including VAT. CE, in 2018, listed the price of electric air source heat pumps as between 6500 and 14500 euros, including VAT. The original source of CE estimates are the price ranges published by Milieucentraal. ETRI predicted, in a report in 2014, that the average price of electric air source heat pumps would fall by 17% between the years 2020 and 2050. The same factsheet states that Ecofys, in 2015, estimated a drop of 33% in the price of heat pumps between the years 2020 and 2050. An average capacity of 6kWth was assumed by Niessink. Maintenance costs were estimated by Startmotor (2018) as 128 euros per year in 2030, no figures after 2050 are available. [40]

In the factsheet for ground source heat pumps, also by TNO in 2019 (by Niessink), states that the Nationaal Warmtepomp Trendrapport (2018) estimated the total investment cost, including installation, of air source heat pumps to be at least 12000 euros including VAT. CE Delft, in 2018, listed the price of electric air source heat pumps as between 8500 and 16500 euros, including VAT. ETRI estimated a drop of 17% in the average price of electric ground source heat pumps. Ecofys estimated a drop of 27% in the average price of ground source heat pumps. All estimates were exclusive of VAT. An average capacity of 10kWth was assumed by Niessink. Adjustments to electric meter boxes were indicated by CE to be 200 euros (one-off), while maintenance costs were indicated to be 50 euros/year. [41] These have been summarized for air and ground source heat pumps, in Table 3.14.

Table 3.14 – Present-day Air and Ground Source Heat Pump Investment Costs

Technology	Price in Euros (Nationaal Warmtepomp Trendrapport)	Price in Euros (CE)	Price Reduction Between 2020 and 2050
Air Source Heat Pumps	5000 to 10000	6500 to 14500	17% to 33%
Ground Source Heat Pumps	At least 12000	8500 to 16500	17% to 27%

Source – Technology Factsheet Heat Pump Air Households, Technology Factsheet Heat Pump Soil Households – TNO

The study "A Review of Domestic Heat Pumps" (2012) highlights the performance of the different types of heat pumps. The highest COP recorded for air source heat pumps is 5.56 at 7°C ambient air temperature, with output of temperature at 25°C. The study conducted its own method of modelling the performance of heat pumps, using the data from various worldwide studies. The average SPF of air source heat pumps was determined at around 2.86, with a 10% decrease in SPF with auxiliary systems in operation. [38]

In general, due to the performance of heat pumps being dependent on the difference in temperature between the heat source and the space to be heated, the COP of heat pumps drops by 0.6 – 1 for every 10°C temperature difference, that is, the COP drops with increasing temperature difference. To maximise heat pump performance, this temperature difference needs to be as small as possible. The study mentions that to improve heat pump performance, the area over which the heat pump delivers heat could be increased, which would lower the output temperature that the heat pump needs to deliver, as in underfloor heating, lowering the temperature difference and increasing the performance. The other method suggested is to improve building insulation, to reduce the amount of heat lost. [38]

A report titled “Commercial Earth Energy Systems: A buyer’s Guide” by the organisation Natural Resources Canada contains data for typical coefficient of performance (COP) values of air and ground source heat pumps based on the temperature lift required, and the type of heating system, i.e. whether the heating is carried out under the floor using underfloor heating coils, or with the use of a radiator. The COP values are detailed in the Table 11. [42]

As seen in Table 3.15, the COP decreases with increasing temperature lift. Underfloor heating requires a lower temperature lift than radiators as a larger surface area is heated up, lowering the temperature lift required to achieve the same temperature within the space to be heated. The COP also indirectly depends on the level of insulation in the dwelling, because for less well insulated dwelling, higher radiator temperatures are needed. The relationship between COP and dwelling insulation is dependent on the specific heat pump and varies from manufacturer to manufacturer.

Table 3.15 - Heat Pump Performance (Present Day)

	35 degree (underfloor)	**45 degree (underfloor)**	**55 degree (underfloor)**
Type of Heat Pump		**COP**	
ASHP - air at 0 degrees	3.8	2.8	2.2
GSHP - water at 4 - 10 degrees	5	4	3.7

Source -“Commercial Earth Energy Systems: A buyer’s Guide” - Natural Resources Canada

For the present study, COP of the heat pump is assumed to decrease with decreasing household insulation quality. Households with insulation label A will require a lower temperature lift than households of insulation label D, in theory, thus, heat pumps will perform better in houses with insulation label A. The COP figures provided by ‘Commercial Earth Energy Systems’ also follow the trend outlined by the report “A Review of Domestic Heat Pumps” – each 10 degree Celsius increase in temperature lift results in a fall in COP by 0.6 to 1. [38] The COP figures in Table 3.15 are thus particularly suitable for use in the present study.

For the Netherlands, in 2050, air source heat pumps are assumed to achieve a COP of 3.8 in households with insulation grade A, and a COP of 1.8 in households with insulation grade D. However, households of insulation label D and lower are assumed to be renovated to label C based on CE’s recommendations. Ground source heat pumps are assumed to achieve a COP of 5 in households with insulation grade A, and 2.4 in households with insulation grade D. It is also assumed that houses with insulation grade D would require the maximum temperature lift and are unsuitable for installing underfloor heating coils, heating is achieved through radiators. All installations are assumed to be new.

Calculating Annual Costs of the Electric Scenario

1) Households of insulation label D, E, F and G are assumed to be renovated to label C according to CE's recommendation by 2050, for the electric heat pump scenario, based on recommendations by CE, and based on renovation cost figures by CE, and annuitized over the lifetime of household insulation (50 years, explained under "Cost of Home Renovations").
2) The annual space heating demand for each household will be met by electric air or ground source heat pumps in 2050.
3) For the domestic hot water demand, water will be heated to 48°C by heat pump at COP 2.75 (CE figure) and then heated to 55°C for the low temperature heating system by a resistive heater of assumed efficiency 0.95 based on [43] statement that the best available electric water heaters have efficiencies of 0.95. COP corresponds with the figure given in "Commercial Earth Energy Systems".
4) Electricity tariffs, as selected before, take into account the levelized cost of electricity generation, storage, transmission and distribution (levelized system cost).
5) Disconnection from gas grid is taken as a one-off fee from Bekhuis' thesis, as 567 euros per household, annuitized over the lifetime of the heat pumps (15 years) gives - 62.34 euros/house/year
6) Reinforcing household electricity grid connection is taken as a one-off fee from Bekhuis' thesis, as 200 euros per household, annuitizing over the lifetime of heat pumps (15 years) gives - 21.95 euros/house/year
7) Investment in Low Temperature heating system is taken as 1540 – 1950 euros per radiator, with a 0.8 cost reduction factor, from Bekhuis' thesis. Annuitized over the lifetime of the radiators (taken as 15 years) gives 170 – 213 euros/house/year (average 192 euros/house/year).
8) Annual operation and maintenance costs for air and ground source heat pumps have been taken from Niessink's technical factsheets for heat pumps and are given at the end of this chapter.

- $Annual\ Energy\ costs\ =\ space\ heating\ costs\ +\ domestic\ hot\ water\ costs$
  Based on electricity tariffs

- $Annual\ costs\ per\ household\ \left(\frac{euros}{year}\right) = Annual\ Energy\ Costs + Cost\ of\ Disconnecting\ from\ the\ Gas\ Grid + Cost\ of\ Reinforcing\ Household\ Grid\ Connection + Investment\ in\ Low\ Temperature\ Radiators + Annual\ Operation\ and\ Maintenance\ Costs\ + Annual\ Insulation\ Costs\ \left(\frac{euros}{year}\right)$ For each type of dwelling in the Netherlands considered in the present study.

- $Total\ Annual\ Cost = Annual\ Cost\ per\ Household\ \left(\frac{euros}{year}\right) * Number\ of\ houses$
  In euros/year

3.9.2 Hybrid Heat Pumps

Hybrid heat pumps essentially combine the function of a heat pump with that of a gas boiler. The hybrid heat pumps currently on the market consist of some configuration of an air-source heat pump, a boiler, and a controller. The heat pump may be either mono bloc air source heat pump, or split. Ground source heat pumps are unlikely to be used in a hybrid configuration according to manufacturers and installers. Their high efficiency and ability to store heat neutralizes the potential cost and peak-shaving benefits of hybrid systems.

Mono bloc and split air-source heat pumps do not differ significantly in performance. Inverter-driven heat pumps have variable compression rates and operate more efficiently than non-inverter driven heat pumps over a wider range of operating conditions. Mono bloc heat pumps are also available in more compact designs which have a smaller footprint compared to non-compact versions, and would therefore be more practical in terms of installation and any required planning permissions. [45]

The study "Hybrid Heat Pumps Final report for Department for Business, Energy & Industrial Strategy" by UK-based Element Energy details the factors affecting the performance of hybrid heat pumps. Hybrid heat pumps are offered in three configurations. In the add-on configuration, an existing boiler has a controller and heat pump added on to it. In the integrated configuration, the boiler, heat pump and controller are packaged and sold a one single unit. In the packaged configuration, the boiler, heat pump and controller are sold as separate products, but are installed together to form a complete unit.

The building type has the biggest impact on both system cost and system performance. The building energy demand will affect the sizing of the heat pumps, the build characteristics will determine the installation techniques needed. Buildings with better insulation will have lower energy demands. Also, the energy demand will be less variable, leading to improved heat pump performance and lower emissions. [45]

Also outlined in the study by Element Energy, were future cost reduction scenarios for hybrid heat pumps by the year 2050. The scenarios were constructed after coordinating with various industry stakeholders, with a high rate of response. For the device capital costs, a large number of stakeholders predicted possible reductions in cost of between 10% and 40%. These reductions are dependent on increasing the volume of hybrid heat pumps in the market, along with reductions in the costs of individual components such as compressors. [45]

The technology is also benefitted by a learning curve, costs are expected to drop as the market expands and the technology becomes mature. The costs are projected to reduce even in the face of increasing efficiency demands from future energy systems. For the device installation costs, costs are expected to reduce by 10% to 70% by stakeholders. These reductions are mainly dependent on increasing sales volumes, selling the heat pumps as pre-integrated devices, and by simplifying the installation process as experience with the technology grows. Based on these results, the study outlined three cost reduction scenarios by the year 2050. For the central scenario, which assumes a moderate rate of growth of the hybrid heat pump market, the study projects reductions of 30% in both capital and installed costs by the year 2050. [45]

The sizing of the heat pump used varies based on the operating conditions of external temperature and output temperature required, for both hybrid, and all-electric heat pumps. The sizing of the heat pump would significantly influence the cost of the overall system. Oversizing the heat pump would enable demand to be met throughout the year. Under sizing would lead to less than 70% demand being met but would also reduce the peak electricity demand, according to the study. Thus, the sizing strongly affects both the system cost and performance. [45]

The type of emitter (low temperature or high temperature) will have a moderate effect on system cost as using existing emitters is cheaper. It has a very strong impact on performance, using low temperature emitters improves the COP and reduces peak electricity demand. The heating schedule employed by the user will also affect the performance of all-electric and hybrid heat pump systems. There are two heating schedules. In the twice a day schedule, where heating is done for 4 hours in the morning and then again for 4 – 10 hours later in the day. The other schedule is continuous heating, in which the building temperature never drops below the indoor average temperature of the heating season in any 24 hour period. The system does not have to work as hard as in the twice a day schedule. The heating schedule will have no effect on the cost of the system, however, it strongly affects the performance – the performance is better in the continuous heating schedule. [45]

The domestic hot water provision will also affect the performance of the hybrid heat pump system. The two ways in which domestic hot water can be provided are either the boiler meets the entire demand without the need of an additional hot water cylinder, or the heat pump works alongside the boiler to provide domestic hot water, an additional hot water cylinder is required. Domestic hot water provision will have a low-to-moderate impact on the system cost, if domestic hot water demand is met by the boiler only. It has a strong impact on performance, when using a boiler only, the performance improves and the peak demand is lowered. When using a combination of heat pump and boiler to meet domestic hot water demand, system costs are increased by a boiler for the heat pump unit, in addition to the main gas boiler. Using only the boiler to meet domestic hot water demand leads to higher system efficiencies and lower peak demand. [45]

Costs of hybrid heat pump systems in the Netherlands are indicated in the Technology Factsheet on Hybrid Heat Pumps by Robin Niessink, for TNO, in 2019. A heat pump capacity of 5kWth was assumed for cost calculations in the factsheet. Ecofys (2015) reported that investment costs (cost of purchasing the heat pump device only) of hybrid heat pumps would drop from 3800 euros (excluding VAT) in 2020, to 2550 euros (excluding VAT) in 2050, for just the heat pump (decrease of 33%). This is similar to the decrease predicted by stakeholders in the UK study (Element Energy). CE (2018) indicates the price of hybrid heat pumps, with cost of boiler included, and including installation and VAT, to be between 4700 – 6700 euros. Maintenance costs are 150 euros per year including boiler maintenance. Startmotor (2018) indicated maintenance costs to be 138 euros/year in 2030, but no figure after 2030 were available. Nationaal Warmtepomp Trendrapport (2018) indicated total cost of hybrid heat pump systems to be between 4000 to 7000 euros in 2018. [46]

Table 3.16 – Current Prices of Hybrid Heat Pumps in the Netherlands

Technology	Price in Euros (Nationaal Warmtepomp Trendrapport)	Price in Euros (CE)	Price Reduction Between 2020 and 2050 (Ecofys)
Hybrid Heat Pumps	4000 to 7000	4700 to 6700	33%

Source – Technology Factsheet Hybrid Heat Pumps, Households, Technology Factsheet Heat Pump Soil Households – TNO

Table 3.17 – Hybrid heat pump performance (Current)

	COP
HHP – 33 degree lift	3.4
HHP – 28 degree lift	4.5

Source -"Hybrid Heat Pumps Final report for Department for Business, Energy & Industrial Strategy" - Element Energy

Table 3.18 – Heating demand met by heat pump (Current)

	Percentage of annual heating demand met by heat pump							Average (%)
HHP DTI Single Family homes	78	75	65	69	53	61	89	70
HHP DTI Multi Family homes	30	96	96					N/A

Source -"Hybrid Heat Pumps Final report for Department for Business, Energy & Industrial Strategy" - Element Energy

The final report for the study "Hybrid Heat Pumps" also lists the performance of hybrid heat pump systems from a range of manufacturers and also using data from prior studies, including the Manchesterbased field trial of more than 400 heat pump systems, made up of a combination of conventional heat pumps and hybrid heat pumps. Like conventional heat pumps, hybrid heat pumps operate more efficiently with better thermal insulation in the buildings. The study also suggests that hybrid heat pump systems perform better when serving a larger number of families. [45] The studies were done for single and multiple family dwellings of various types (flats, detached houses and terraced houses).

In Table 3.18, the columns under 'Percentage of annual heating demand met by heat pump' show the percentage of the annual space heating demand per dwelling that has been met by DTI brand hybrid heat pumps of various configurations in single and multiple family homes. The values for multiple family houses are too varied to take a meaningful average. However, the study also modelled hybrid heat pump performance under both heating schedules, for a variety of configurations. For all the modelled cases with continuous heating schedules, the heat pump met 70 – 85% of the annual space heating demand. Modelling was done to calculate space heating demand alone, daily hot water usage was found to be largely constant for a particular dwelling throughout the year. [45]

The study by Element Energy was performed for the UK, with the published COP figures being the result of field trials of actual hybrid heat pump systems. A similar review of Dutch hybrid heat pumps is not available. The residential space heating of the UK is currently based almost entirely on natural gas, with gas being supplied to households via pipelines, as is the case in the Netherlands. For the purpose of the present study, the performance of the hybrid system in terms of COP needs to be known to calculate the annual cost of energy to the end consumer. In addition, the COP of the hybrid system is also dependent on the household insulation quality, higher insulation quality leads to higher COP, thus lower annual costs. [45]

According to the technology factsheet on hybrid heat pumps, CE (2018) figures for hybrid heat pump performance (COP) are, on average, 3.5 – 4.5, for a supply temperature below 55°C (space heating). For domestic hot water, the COP range was 2 – 2.6. Startmotor (2018) figures for performance (COP) are indicated as 3.5 for space heating, and 2 for domestic hot water, by 2020. Niessink's assumptions in the factsheet put the COP = 3.5 by 2020, 4 by 2030 and 4.5 by 2050. Efficiency of the condensing boiler was 0.9 for space heating, and 0.72 for domestic hot water, with the boiler providing the entire domestic hot water demand, according to Startmotor. [46]

The factsheet for hybrid heat pumps also lists performance characteristics of hybrid heat pump systems in the Netherlands, as reported by various organisations. According to Niessink, Greenhome, (2018) stated that in households with a beta factor of 0.4 or higher (high quality of household insulation), 90% of space heating demand would be met by the electric heat pump. For moderate insulation quality (beta factor 0.2), 60% of the space heating demand would be met by the heat pump, and for households with poor insulation quality (beta factor<0.1), 30% of annual space heating demand would be met by the heat pump. [46]

$$Beta\ factor\ = \frac{capacity\ of\ the\ heat\ pump(kW)}{transmission\ of\ the\ dwelling\ envelope\ (kW)}$$

Calculating Annual Costs of the Hybrid Scenario

1) 90% of the annual space heating demand per household in 2050 is assumed to be met by the electric air or ground source heat pump (COP 4.5 based on Niessink and Element Energy figures), based on Niessink's technical factsheet, 10% met by hydrogen boiler (0.97 efficiency based on HHV), for houses of label A (assumed high beta factor). Since the boiler component is assumed to be hydrogen fired in the present study for the year 2050, the efficiency of a hydrogen boiler is used for the hot water demand, expanded in the 'End-Use Hydrogen Boilers' section.

2) 60% of the annual space heating demand is assumed to be met by the electric air or ground source heat pump (COP 4.5), based on 40% met by hydrogen boiler (0.97 efficiency based on HHV, see Appemdix), for houses of label B, C (assumed moderate beta factor).
3) 30% of the annual space heating demand is assumed to be met by the electric air or ground source heat pump (COP 3.5 based on Niessink and Element Energy), based on 70% met by hydrogen boiler (0.97 efficiency), for houses of label D, E, F and G (assumed low beta factor).
4) Domestic hot water demand per household in 2050 is assumed to be met entirely by hydrogen boiler with an efficiency 0.82 for all insulation levels. The efficiency is lower than for space heating as the temperature lift required is higher for domestic hot water demand.
5) Electricity tariffs, as selected before, take into account the levelized cost of electricity generation, storage, transmission and distribution (levelized system cost).
6) Energy costs = space heating costs + domestic hot water costs, based on electricity and hydrogen tariffs
7) Reinforcing household electricity grid connection is taken as a one-off fee from Bekhuis' thesis, as 200 euros per household, annuitizing over the lifetime of heat pumps (15 years) gives - 21.95 euros/house/year
8) It is also assumed that in households with high-moderate beta factor, investment in Low Temperature heating system will be required as the heat pump is assumed to meet more than half the annual space heating demand in these households. The costs are taken as the same as the costs for the all-electric heat pump scenario – 170 – 213 euros/house/year for houses of insulation label A to C. (using cost reduction factor 0.8 by 2050 according to Bekhuis in [10]).
9) Annual operation and maintenance costs for hybrid heat pumps have been taken from Niessink's technical factsheets for hybrid heat pumps and are given at the end of this chapter.

- $Annual\ Energy\ costs\ =\ space\ heating\ costs\ +\ domestic\ hot\ water\ costs$ Based on electricity and hydrogen tariffs

- $Annual\ costs\ per\ household\ \left(\frac{euros}{year}\right) = Annual\ Energy\ Costs + Cost\ of\ Reinforcing\ Household\ Grid\ Connection + Investment\ in\ Low\ Temperature\ Radiators + Annual\ Operation\ and\ Maintenance\ Costs\ + Annual\ Insulation\ Costs\ \left(\frac{euros}{year}\right)$ For each type of dwelling in the Netherlands considered in the present study.

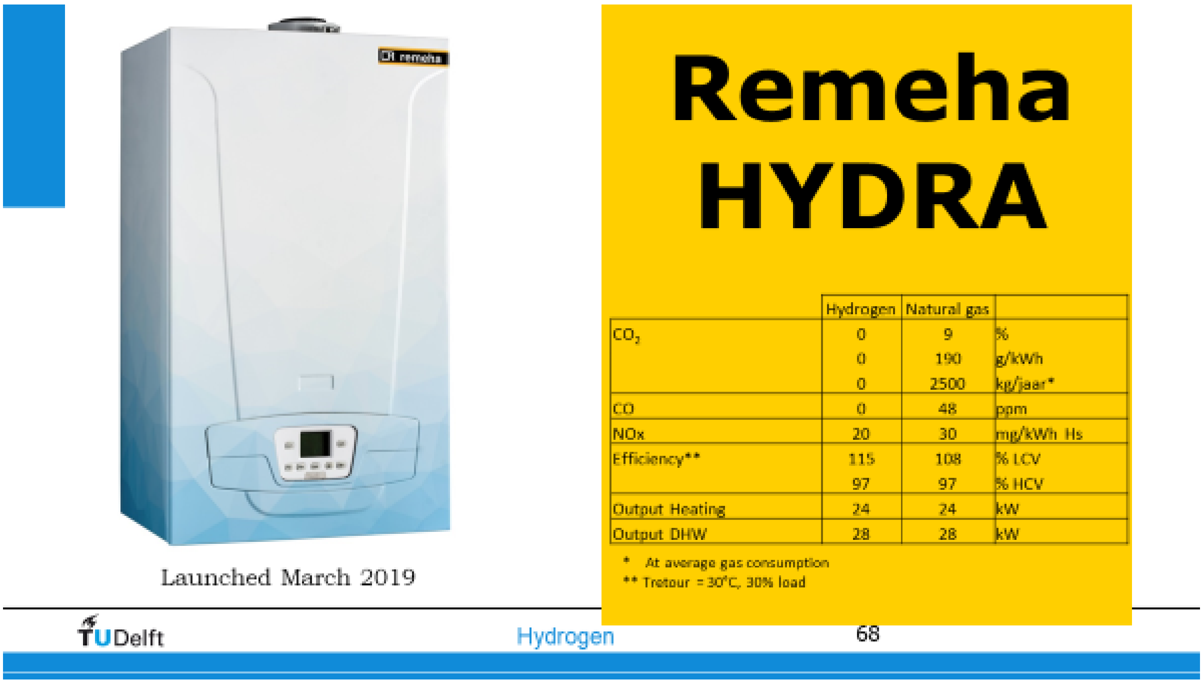
- $Total\ Cost = Annual\ Cost\ per\ Household\ \left(\frac{euros}{year}\right) * Number\ of\ houses$ In euros/year

3.9.3 End-Use Hydrogen boilers

In 2012, the first boiler that can combust hydrogen to produce heat was developed by the UK based Giacomini. The developed device uses a self-priming catalyst in order to activate the reaction between hydrogen and oxygen to produce heat. The device does not require electricity to start the reaction. Due to the low reaction temperatures of 300°C, there are no harmful NO_x emissions, the only by product of the reaction is water vapour. The boiler has a nominal capacity of 5kW. [47] The boiler installed costs (capital cost plus installation cost) are estimated to be around £15000 (€17675). [48]

The world's first residential hydrogen powered heating system was deployed by BDR Thermea in Rozenberg, The Netherlands, on 25 June 2019. The boiler utilises hydrogen that is produced from solar and wind energy. [49] In a study carried out by Northern Gas Networks, Wales and West Utilities, KIWA, and Amec Foster Wheeler, the cost of appliance conversion from gas to hydrogen for 2500 properties in the city of Leeds, UK, was estimated to be €2850/property, including installation, and excluding overheads and tax. The cost of the hydrogen boiler was taken as 945 euros/unit for the hydrogen boiler, 334 euros/unit for the hydrogen cooker, and found the average appliance cost per property to be 1914 euros. [50]

According to theheatinghub.co.uk, fitted natural gas boiler costs range from £1400 – £3500 (€1649.73 – €4124.3), with the actual boiler cost ranging from £685 – £1150 (€807.19 – €1355.14). [51] For the present study, it is assumed that with technological developments and the establishment of a hydrogen economy for the hydrogen and hybrid scenarios, hydrogen boiler overall costs in 2050 will not be much higher than that of present gas boilers. Boilers are also assumed to have an overall conversion efficiency of 0.97, of HHV, as gas boilers in the Netherlands have efficiencies of approximately 0.97 of HHV. In "Lifecycle cost and CO2 emissions of residential heat and electricity prosumers in Finland and the Netherlands" (2018), O&M costs for NG boilers was given as 130.44 euros per year. [52] All installations are assumed to be new, cost of disposal of the old boiler is not taken into account.



	Hydrogen	Natural gas	
CO_2	0	9	%
	0	190	g/kWh
	0	2500	kg/jaar*
CO	0	48	ppm
NOx	20	30	mg/kWh Hs
Efficiency**	115	108	% LCV
	97	97	% HCV
Output Heating	24	24	kW
Output DHW	28	28	kW

* At average gas consumption
** Tretour = 30°C, 30% load

Fig. 3.1 – Remeha Hydra Boiler Factsheet

Figure 3.1 gives the technical specifications of the Remeha hydrogen boiler.

Calculating Annual Costs of the Hydrogen Boiler Scenario

1) Annual space heating demand is assumed met by hydrogen boiler with efficiency of 0.97 based on HHV in 2050 (see Appendix).
2) Domestic hot water demand is also assumed to be met by hydrogen boiler, efficiency 0.82 according to Bekhuis
3) Households are still assumed to be connected to the electricity grid for household appliances, only space heating is achieved by hydrogen combustion.
4) Energy costs = space heating costs + domestic hot water costs, based on hydrogen tariffs
5) Annual Operation and maintenance costs of hydrogen boilers in 2050 are assumed to be the same as current gas boiler O&M costs, taken from "Lifecycle cost and CO2 emissions of residential heat and electricity prosumers in Finland and the Netherlands"

- $Annual\ Energy\ costs\ =\ space\ heating\ costs\ +\ domestic\ hot\ water\ costs$ Based on hydrogen tariffs

- $Annual\ costs\ per\ household\ \left(\frac{euros}{year}\right) = Annual\ Energy\ Costs + Cost\ of\ Reinforcing\ Household\ Grid\ Connection + Investment\ in\ Low\ Temperature\ Radiators + Annual\ Operation\ and\ Maintenance\ Costs\ + Annual\ Insulation\ Costs\ \left(\frac{euros}{year}\right)$ For each type of dwelling in the Netherlands considered in the present study.

- $Total\ Cost = Annual\ Cost\ per\ Household\ \left(\frac{euros}{year}\right) * Number\ of\ houses$ In euros/year

3.9.4 Summary of Device Performance Factors

- Heat pumps are electrical devices, used in the all-electric pathway. They can either be air-source heat pumps or ground source heat pumps based on the heat source. The coefficient of performance (COP) is the quantity that indicates the heat pump performance, higher the COP, better is the performance. The COP is dependent on the temperature difference between the dwelling and ambient air, the higher the temperature difference, the lower the COP. It also directly depends on building thermal efficiency.
- Ground source heat pumps have a higher COP than air source heat pumps, however, they are often twice as expensive to install. Underfloor heating coils improve the COP compared to radiators as they require a lower temperature difference, however, they can be more expensive to install. Heat pumps also require good thermal insulation of the dwelling in order to maximise the COP.
- Hybrid heat pumps combine the functioning of a heat pump with a gas boiler. The gas boiler is used to meet peak load demand. The COP of a hybrid heat pump is affected by the same factors as all-electric heat pumps. Over 70% of the heat demand is met by the electric heat pump component. Heat pump sizing and building heat demand are the factors that have the biggest impact on cost.
- Hydrogen boilers are still an emerging technology, with real world trials being undertaken as of 2019, as implementation in households will require testing mainly for safety reasons, to prevent fires and because hydrogen is lighter than natural gas, and odourless.

3.10 Cost of Home Renovations

As stated earlier in this report, heat pumps need to be combined with improved insulation measures in households, in order to maximise the COP during the heating season. The study “Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – Update 2016” by the consultancy CE Delft, costs related to improving building insulation were calculated using the CEGOIA model, for two configuration of floor area – ground bound (used for insulation costs of terraced, semi-detached, and detached houses in this study) and stacked (used for insulation costs of low and high rise flats). The insulation costs are given for single step improvements in insulation label class, from label G to label A++. The insulation step improvement values are shown in Table 3.19. [53]

The cost of renovations to improve household insulation needs to be taken into account to calculate the total annual cost per household for each scenario, as heat pumps require high levels of insulation to maximise the COP. In addition, even the hydrogen scenario would benefit from improvements to household insulation, current methods of reducing household energy expenses in the Netherlands is by improving household insulation levels. The study conducted by CE Delft, outlined in Table 12, was the only one found to calculate insulation label improvements in steps for the Netherlands.

Other studies, and even the CE Delft study, mention that the overall costs of improving household insulation levels would be around €28,000 per household, however, the time frame of analysis, rate of interest used, annuity factors, and the cost per household per single step improvements in insulation label, were not provided, making it impossible to calculate the cost of home renovations from this cost value. Furthermore, an exact idea of household insulation improvement costs is not possible to determine without analysing the physical walls of the dwelling, such a detailed analysis is out of the scope of the present study.

It is also more useful, for the scope of the present study, to investigate the annual cost of renovations per household per unit area for each step improvement of the insulation label – it is more useful to investigate the energy savings and overall cost for each step improvement in household insulation levels for each of the three scenarios. For these reasons, and the lack of detailed statistical data on household insulation levels in the Netherlands, the cost data for improving household insulation labels in steps from the study by CE Delft have been used.

Table 3.19 - Insulation costs in euros/m^2

	To: A	B	C	D	E	F
From: G	170	140	123	96	66	33
F	166	128	106	72	35	
E	147	107	85	49		
D	122	76	49			
C	185	69				
B	70					

Source - “Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving – Update 2016” by CE Delft

According to the report “Comparative Assessment of Insulating Materials on Technical, Environmental and Health Aspects for Application in Building Renovation to the Passive House Level” (Melchert Duijve), household insulation lifetimes are typically 50 years. [54] This lifetime has also been chosen for this study. Other sources such as Reenergizeco show the insulation lifetimes to range from 30 years to 80 years, 50 years seems a reasonable lifetime. [55]

3.11 Selecting Investment Costs for Boilers, Heat Pumps and Hybrid Heat Pumps

The investment cost for hydrogen boilers is taken as €1433, from the figure in the study by Northern Gas Networks, which take into account modifications that need to be made to utilise hydrogen. Subtracting VAT of 21% gives the investment cost of 1132 euros. This source was used it was the most comprehensive and complete sources, with no equivalent studies on the Dutch scenario available. Cost data and the method of calculations done in each study mentioned in the sources have been detailed, including the methodology of field trials. Maintenance costs taken as 130.44 euros/year, from the O&M costs of gas boilers.

For air and ground source heat pumps, the technical factsheets by TNO are used as sources as they give the most recent cost estimates for the Netherlands including the installation costs, which are absent from other sources. For air source heat pumps, the range of 10000 euros to 14500 euros, the upper limit of the investment cost range from the studies reviewed earlier, is used as the cost range, including installation cost, the average of which is 12250 euros; subtracting VAT gives us 10208 euros. Assuming a 17% decrease in investment cost by 2050, from the factsheet, gives us 8473 euros (overall costs will be calculated for 33% decrease as well, detailed in the ‘Sensitivity Analysis’ chapter).

For ground source heat pumps, the range of 12000 to 16500 euros, the upper limit of the investment cost range from the studies reviewed earlier, is used, including installation cost, the average of which is 14250 euros; subtracting VAT gives us 11875 euros. Assuming a 17% decrease in investment costs by 2050 gives 9856 euros (will be calculated for 27% decrease as well, expanded in ‘Sensitivity Analysis’). For all heat pumps, the annual cost per household will also be calculated when the lower end of investment costs in the range are taken as well. Maintenance cost figures from these factsheets will be used as well – 128 euros/year for air source, and 50 euros/year for ground source heat pumps.

For hybrid heat pumps, the figures from Niessink's technology fact sheet are again used. Average investment costs of 5500 euros are taken, from the range presented in the factsheet. Assuming a 30% reduction in investment cost by 2050 and excluding tax, we get investment costs of 3041 euros/device. Maintenance costs are taken from the factsheet to be 138 euros/year. All maintenance cost figures for heat pumps are based on 2030 values, values for 2050 were not found.

Table 3.20 - Investment costs and device lifetimes for boilers, heat pumps and hybrid heat pumps (2050)

Type of home	Hydrogen Boiler	ASHP	GSHP	HHP
Cost Per Unit Area (euros/m^2)	9	66(25)	77(49)	24
Device Lifetime (years)	15	15	15	15

Table 3.21 - Investment costs in euros for boilers, heat pumps and hybrid heat pumps (2050)

Type of home	Hydrogen Boiler	ASHP	GSHP	HHP
Terraced	1132	8473	9856	3041
Flat - Low Rise	608	4455	4928	1620
Flat - High Rise	864	4032	7008	2304
Semi-Detached	1260	6636	10220	3360
Detached	1422	10428	11534	3792
Device Lifetime (years)	15	15	15	15

Table 3.22 - Annual O&M Cost per Device (for 2050)

	ASHP	GSHP	HHP	Hydrogen Boiler
Annual Maintenance Cost (euros/year)	128	50	138	130

The cost per unit area is useful for calculation purposes in the model. It also allows us to investigate the cost of each technology per dwelling. The actual cost of the device per unit area depends on the capacity of the heating system, the installation techniques used, and even the brand of device. These factors are not useful to include as they are not within the scope of the present study. For a national outlook, to provide a first order estimate of cost in a generalised manner, it is assumed in the present study, that the cost of each device per unit area is the same for every type of dwelling. In reality, both, the overall cost, and the cost per unit area vary, such detailed data is not available, as is the case with housing data of other types, mentioned earlier in this report.

The assumptions are detailed in Table 3.21. Terraced houses are the most common type of dwelling in the Netherlands (41% of dwellings). Terraced houses are also intermediate between detached houses and low rise flats in terms of floor area. For the present study, in Table 3.20, the cost per unit area for terraced houses, with area $128m^2$ has been used as the basis for the cost per area for all dwellings. Flats (low and high-rise), terraced houses and semi-detached houses are taken as multiple family home configuration, with detached houses being single family homes. Lifetime of each device is taken as 15 years. Table 3.21 gives the investment cost per type of dwelling in terms of euros. These investment costs have been annuitized over the lifetime of each device (15 years, as given in Table 3.21).

4. Hydrogen Transport and Storage Infrastructure in Netherlands

According to “Outlines of a Hydrogen Roadmap” by TKI Nieuw Gas the Netherlands has been using hydrogen as an industrial feedstock for a number of decades. A large hydrogen network, which covers around 1,000 km in length, connecting Rotterdam, Zeeland, Belgium and the north of France has been built by the private company Air Liquide. Air Liquide also owns a second large private network, located just across the border, in the Ruhr area. There is also a hydrogen network of approximately 140 km in the Rotterdam region, which is owned by Air Products. [20]

The study “Hydrogen Admixture in the Dutch Gas Grid” by TNO in collaboration with the University of Amsterdam, goes into detail about the Dutch gas transport grid. The gas transport network for onshore applications in Netherlands is operated by Gasunie (GTS). It is made up of 12000 km of transport pipelines with the necessary connection points, compressors and mixing stations. The transport network is divided into two parts. The main transport system (HTL) is connected to natural gas manufacturers, industries, power plants, gas storage facilities and gas import locations. The regional transport system (RTL) is connected to distribution systems operators, smaller industries and power plants. The HTL feeds into the RTL. Each system has its own design codes and maximum allowances. The distribution grid is divided into the high pressure distribution grid (HDD) and the low pressure distribution grid (LDD). It consists of about 130000 km of pipes, of which 60% are made from PVC. It connects the RTL to consumers’ homes, and provides gas for heating and cooking. [56]

The existing high-pressure natural gas network of Gasunie Transport Services (HTL) consists mainly of pipelines, compressor stations and measurement and pressure control stations and gas storage. This network can sufficiently transport energy to every end user, and is also used for storage (line pack) to quickly meet an expected demand in the very near future (often within 1 day). [3]

4.1 Comparing Hydrogen and Natural Gas

It is important to know what the transport capacity of hydrogen is compared to natural gas, which can be used to determine the amount of energy in the network. The energy content (upper calorific value) of hydrogen is approximately a third of that of natural gas, at 12 MJ/Nm^3, while that of high calorific natural gas (so-called H-gas) is approximately 40 MJ / Nm^3 (or approximately 35 MJ / Nm 3 for Groningen gas, all HHV).

For hydrogen to meet the same energy requirement are as for natural gas the volume of hydrogen to be transported must be three times as large. Pressure drop is the critical parameter for dimensioning a pipeline network. The most important parameter that affects the pressure drop is the density of hydrogen relative to natural gas. The density of hydrogen is nine times lower than that of natural gas. Because the pressure drop is inversely proportional to the root of density, a flow of hydrogen with a volume three times larger than natural gas, will have approximately the same pressure drop. [3]

4.1.1 Transporting Hydrogen

There are other parameters that also vary with pressure or flow rate and have some influence on pressure drop or transport capacity. Detailed calculations indicate that utilising hydrogen in an existing gas pipeline, for the same pressure drop, will transport 98% of the energy as compared to Groningen gas and 80% in comparison with high-calorific natural gas (H-gas), which can be compensated for by lowering the energy demand at the end-user site. To get the same energy transport capacity, hydrogen needs to move through the pipelines at higher speed than gas.

These high speeds can lead to vibration problems and erosion. The severity of vibration problem depends on the speed of the flow gas, the density and the speed of sound in the medium. The density of hydrogen is lower than that of natural gas and therefore the effect of higher speed is largely compensated, so the transition from natural gas to hydrogen has little or no effect on the occurrence of vibration problems. Erosion is caused by the fact that solid particles that are transported in the network and at higher speeds increase the risk of erosion. [3]

4.1.2 Storing Hydrogen

Gas is stored in the existing gas transport system in empty gas fields and in salt caverns. The transition to 100% hydrogen reduces the storage capacity of energy. At the same volume of a cavern, due to the lower energy density of hydrogen the energy content will be a third of the storage capacity of the cavern if natural gas were to be used. Storage of hydrogen in caverns seems quite possible, but storage in old gas fields may pose initial problems. Due to the remaining natural gas in the fields that have not been exhausted, pollution of the stored hydrogen gas occurs which entails additional costs for cleaning.

Another factor that determines the feasibility of hydrogen storage in disused oil fields is whether the field can adequately contain the hydrogen; the small hydrogen molecule could possibly diffuse away very easily in the absence of suitable containment. As with gas storage, the same conditions apply to line pack in the pipeline network. Here same volume flow is maintained, but with only a third of the energy content, making anticipating variations in energy demand difficult. Thus, taking into account the energy content of hydrogen and natural gas, the line pack energy from hydrogen may in some cases be more than four times smaller than that from natural gas. [3]

According to the report "Outlook for a Dutch Hydrogen Market - Economic Conditions and Scenarios" by Mulder, Perey and Moraga, the methods of hydrogen storage that have been proven and actually used are pressurised, small scale storage tanks for intra-day storage, and large scale storage in empty salt caverns. Small scale storage tanks are mainly for use at hydrogen production stations themselves, while salt cavern storage is for long-term storage applications. They are compared in the Table 4.1.

Table 4.1 – Comparison of Hydrogen Storage Technologies

	Tanks	**Salt Caverns**
Type of storage	Intraday	Seasonal
Capacity	45 MWh/tank	150 GWh
Investment costs	N/A	€30 million
Cushion gas costs	N/A	€4.98 million
Cushion gas amount	N/A	140 GWh of working gas

Source -"Outlook for a Dutch Hydrogen Market - Economic Conditions and Scenarios" by Mulder, Perey and Moraga

The capacity of each tank is equal to the amount of gas used annually by three Dutch households in three days. The storage capacity of a salt cavern is typically equivalent to the amount of gas required for 10000 Dutch households annually. Storage in depleted gas fields has not been proven yet. The capacity of storage depends on the volume of hydrogen that can be stored in the salt cavern (the working volume), and the rate of hydrogen injection and withdrawal from the storage facility in a specific period of time. The cushion gas investment for salt cavern storage is a particular type of investment that is dependent on the cushion gas, which is the permanent volume of hydrogen gas required within the storage facility in order to maintain adequate operational pressure. [57]

4.2 Using Hydrogen in the Existing Natural Gas Grid

Studies done in the past have shown that the existing natural gas pipelines can potentially be used to transport hydrogen, by paying careful attention to failure mechanisms, crack propagation in the pipeline materials, along with the devices used for control and monitoring. [3]

4.2.1 Degradation and Failure Mechanisms

The use of hydrogen in natural gas pipelines may lead to degradation and failure of the pipeline materials. Hydrogen, unlike natural gas, can lead to hydrogen embrittlement in pipelines. For the pipelines which are used, constructed and controlled in the Netherlands, this will not create significant problems when using hydrogen in the existing natural gas grid. Hydrogen can, however, affect the fatigue behaviour of steel and this can degrade the lifetime of pipelines at varying pressures. However, many varieties of steel with varying carbon content are used in worldwide hydrogen transport. As long as the issue of different fatigue behaviour of steel under different pressures of hydrogen are recognized, and suitable measures are taken into account, hydrogen transport can be carried out in a safe and reliable manner. [3]

The main measure that needs to be taken is preventing internal corrosion and erosion of pipeline material by the hydrogen flow. To prevent internal corrosion and to reduce erosion as much as possible, it is important that the gas being transported through the gas grid pipes be clean and dry gas (water dew point is below 60% in all circumstances of relative humidity). Test programs by NaturalHy have shown higher fatigue crack growth rate when transporting hydrogen through natural gas pipelines. This can be overcome by checking the operational conditions carefully, and by limiting pressure fluctuations during operation. [3]

4.2.2 Crack Propagation in Case of Pipe Breakage

Natural gas pipes must have sufficient resistance to crack propagation. Therefore natural gas pipelines are designed to stop a break within a limited pipeline length. It is essential that in front of the site of a crack in the pipeline material, decompression rate of the gas is greater than the speed of propagation of the crack in the pipe, that is, rate of flow of gas in the pipe should be higher than the speed of crack propagation. Decompression speed is higher when transporting hydrogen than natural gas. This higher decompression rate has a favourable effect on stopping the crack propagation in the event of a pipe break, thereby reducing the chance of crack propagation when a natural gas pipeline is converted to hydrogen, at the same time pressure. From an integrity point of view, the current gas network can be used perfectly for the transport of hydrogen and also mixtures of natural gas with hydrogen. More stringent monitoring can ensure that the operating conditions are within the limits of fatigue crack growth. [3]

4.2.3 Compressors, Pressure Control Stations and Measuring Stations

Existing compressors are not automatically suitable for 100% hydrogen. The degree of adjustment/replacement will have to be checked. In the conventional gas grid, two types of compressors are used, reciprocating piston compressors, and rotational centrifugal compressors. In principle, the gas used in the piston compressor is of no consequence to operation, however, it still needs to be tested whether the piston compressors can support the use of 100% hydrogen.

Hydrogen requires 3 times the volume of compression for the same energy content (the density is three times lower than that of natural gas). With centrifugal compressors, the required rotational speed is 1.74 times the speed required for compressing the same volume of natural gas. Higher rotational speeds give rise to higher material stresses, for which the current centrifugal compressors are not designed. Thus, the compressors used in the existing natural gas grid would have to be modified or replaced, to a greater or lesser extent, in order to use 100% hydrogen through the existing gas grid, or could potentially operate at lower capacities. [3]

Hydrogen follows the negative Joule-Thomson effect, the gas heats up on expansion. In the current gas grid, pressure control stations need to heat the natural gas periodically as it cools upon expansion. With the negative Joule-Thomson effect of hydrogen, this additional heat does not need to be supplied externally, so this does not pose a barrier to utilising 100% hydrogen. For measuring stations, to measure the quality of the gas in the pipelines, the current infrastructure is likely not suitable for ensuring the quality of hydrogen in place of natural gas. The new devices needed could potentially be simpler than the current devices when transporting 100% hydrogen (less complex gas composition than natural gas).

Based on current regulations, introducing hydrogen into the gas grid would not pose significant risks that would make it impossible to use hydrogen in these pipelines. Knowledge of failure behaviour and consequences indicate that practice could lead to much smaller problems, or even prove favourable to hydrogen use. [3]

4.3 Studies on Gas Distribution Networks

A study done by Albert van den Noort et al, of DNV GL exploring the gas distribution infrastructure of Netherlands found that the high pressure gas distribution pipelines by Gasunie are suitable for carrying 100% hydrogen, with small changes in operation devices such as meters and operating conditions such as pressure. The report concludes with hydrogen being a suitable energy carrier for future systems. [3] The report 'Future-Proof Distribution Systems' by Rene Hermkens et al. concludes that the existing gas network can be suitable for hydrogen transport if certain additional safety measures are taken in the operation and handling of hydrogen. [18]

Utilising the current natural gas network in the Netherlands could represent a significant reduction in overall costs associated with the transition to zero carbon heating. From the results of the studies on the gas transport infrastructure of Netherlands, it can be seen that the current transport infrastructure is largely suitable for transporting 100% hydrogen with relatively minor modification needed for safety of operation. As such, in the present study, hydrogen will be directly transported to each end-user site via the natural gas transport network in the hydrogen and hybrid heat pump scenarios.

5. Annual Costs per Household

The energy system of the Netherlands is assumed to be 100% renewable energy based, with energy generation coming from a combination of solar photovoltaics, wind turbines, and other renewable energy sources. For the hybrid and hydrogen scenarios, hydrogen is assumed to be produced by dedicated offshore wind turbines in the North Sea and transported via pipelines, to distribution centres. The current Dutch natural gas distribution grid is assumed to be used to transport 100% green hydrogen to households in 2050.

The model created for this study takes cost data of the various decarbonisation technologies, and the electricity and hydrogen tariffs, and gives the total annual cost per household for each insulation grade in 2050. The annual costs per household are made up of the annual energy cost per household, based on annual heating demand, and the annual investment, installation and maintenance costs of each device. First, the energy requirements per home per year for 2050 have been presented in Tables 5.1 – 5.4.

Due to the high degree of uncertainty regarding the investment costs and the future prices of electricity and hydrogen in 2050, the annual costs per household for each decarbonisation device are analysed to investigate which factors contribute most heavily towards the overall annual cost per household. Effects of reductions in household renovation costs and cost of low temperature radiators by 2050 on the total annual cost per household for terraced houses in 2050 are also investigated and presented in this chapter. In all tables and figures, ASHP refers to air source heat pumps while GSHP refers to ground source heat pumps, HHP refers to hybrid heat pumps and HB to hydrogen boilers.

5.1 Annual Space Heating and Domestic Hot Water Requirement per Home

First, the annual space heat demand for 2050 was calculated in kWh for each of the five types of homes in the Netherlands – terraced houses, low and high-rise flats, detached, and semi-detached dwellings for household insulation levels corresponding to insulation grades A to G in the Dutch housing insulation grading system, based on the assumptions outlined in 'Model Inputs and Methodology'. For the heat demand calculation, it is assumed that the entire dwelling is to be heated for the full duration of the heating season for all insulation grades. The calculation method is a general methodology used for system design and energy policy purposes. The annual domestic hot water demand per dwelling for 2050 as calculated in the present study is a function of the number of people per dwelling and the annual domestic hot water demand per person per dwelling.

In general, the heat demand increases with decreasing quality of insulation in 2050 – dwellings with insulation grade A show the least annual heat demand, while dwellings with insulation grade G show the highest annual heat demand. Demand is not equal amongst dwelling types – high-rise flats show the lowest annual heat demand for 2050, while detached houses demand the most heat annually. These findings are attributed to the differences in building geometry and area to be heated. Detached houses have the highest surface area to volume ratio in addition to being the largest in general, with flats having the lowest surface area to volume ratio. The lower the surface area to volume ratio, the lower is the quantity of heat lost from surfaces such as walls, floors, ceilings and windows.

Similar findings are also outlined in the report "Predicting energy consumption and savings in the housing stock - A performance gap analysis in the Netherlands" by Dasa Majcen, - Detached dwellings have the highest actual energy consumption, while flats have the lowest energy consumption levels. The report also states that detached houses have the least favourable shape for heat conservation, and have a greater rate of heat loss through ventilation as compared to flats, however, in the present study, the effect of ventilation is not included, a standard ventilation rate for residences in the European Union have been used. [35]

Detached and semi-detached houses have a greater number of heat exchanging surfaces than individual flats – for detached and semi-detached dwellings, the number of walls that exchange heat with the ambient air is greater than for flats, leading to a higher rate of heat loss within the same insulation grade. Furthermore, the calculated annual heat demand per dwelling in 2050 was higher for terraced houses than for semi-detached dwellings, even though terraced houses were assumed to have a smaller floor area. Under the assumptions of building geometry chosen for this study, the shell volume of a terraced house with 15 individual dwellings was taken as $6750m^3$. This puts the volume of each dwelling at $450m^3$ per dwelling. For semi-detached dwellings, it was assumed that each semi-detached house of volume $810m^3$ would have two sub-dwellings of $405m^3$ each. The greater volume to be heated for terraced dwellings gives rise to greater annual heat demands than semi-detached dwellings. The same reasoning was found to explain the lower annual space heat demand for high-rise flats when compared to low-rise flats.

In the section 'Model Inputs and Methodology', it was stated that in the present study, households of insulation label D and lower would be renovated to insulation label C while using all-electric heat pumps, based on the recommendations by CE and the requirement of a low temperature heating system (radiators) to be installed with the heat pump, in 2050. The annual heat demand per household in 2050 in the all-electric heat pump scenario has been given in Table 5.2. Since households that have been renovated to insulation label C have been assumed to have the same energy consumption as a regular household of insulation label C, the costs have only been shown till houses of insulation label C. Households of label D and lower that have been renovated to label C have the same energy consumption as households of insulation label C. Households that were already at insulation label C require no renovations.

For comparison, in the study "Average EU building heat load for HVAC equipment" by Kemna, the average annual space heat demand per household (excluding domestic hot water demand) for the EU was calculated to be 8214 kWh, taking the average of all the different types of dwellings for the whole EU. [31] No figures for annual space heating demand per household in other studies, or the Netherlands in particular, were found. Table 5.1 gives the annual heat demand per dwelling in kWh/m^2 for the hybrid and hydrogen pathways. In Tables 5.1 – 5.4, DHW refers to annual heat demand due to domestic hot water requirement in 2050. Columns labelled A to G in Tables 5.1 and 5.3 (A to C in Tables 5.2 and 5.4) show space heating requirement only.

Table 5.1 – Annual heat demand per home in kWh for different dwelling types and energy labels – Hydrogen and Hybrid option (2050)

Type of Home	A	B	C	D	E	F	G	DHW
Terraced	7271	9135	10766	12397	30992	38740	46488	2735
Flats – Low-rise	5373	6278	7069	7861	19653	24565	29478	1881
Flats – High-rise	4101	4663	5153	5642	14105	17631	19323	2394
Semi-detached	6777	8642	10273	11904	29760	37200	44640	2735
Detached	7593	10154	12395	14636	36590	45737	54885	2736

Annual space heat demand per home per unit area in 2050 has been given in Tables 5.3 and 5.4, for clarity and to make comparison easier. The area per dwelling has been outlined in the 'Building Volumes and Surface Area' section in ''Model Inputs and Methodology. The same household assumptions for the heat demand per dwelling apply here.

Table 5.2 – Annual heat demand per home in kWh for different dwelling types and energy labels – All-electric heat pump option (2050)

Type of Home	A	B	C	DHW
Terraced	7271	9135	10766	2735
Flats – Low-rise	5373	6278	7069	1881
Flats – High-rise	4101	4663	5153	2394
Semi-detached	6777	8642	10273	2735
Detached	7593	10154	12395	2736

Table 5.3 – Annual heat demand per home in kWh/m^2 for different dwelling types and energy labels – Hydrogen and Hybrid option (2050)

Type of Home	A	B	C	D	E	F	G	DHW
Terraced	56	71	85	97	242	302	363	21
Flats – Low-rise	80	93	105	61	153	192	230	28
Flats – High-rise	43	49	54	58	110	138	150	25
Semi-detached	49	62	73	85	232	290	348	20
Detached	48	64	78	93	286	357	428	17

Table 5.4 – Annual heat demand per home in kWh/m^2 for different dwelling types and energy labels – All-electric heat pump option (2050)

Type of Home	A	B	C	DWH
Terraced	56	71	85	21
Flats – Low-rise	80	93	105	28
Flats – High-rise	43	49	54	25
Semi-detached	49	62	73	20
Detached	48	64	78	17

5.2 Annual Costs per Household Including Renovation Cost to Improve Household Insulation

The annual cost per household in 2050 in the Netherlands, in euros, have been shown for the most common type of dwelling in the Netherlands – terraced houses (40% of the current housing stock, according to CBS Statline). [58] The costs have been compared for each of the three chosen decarbonisation technologies - electric air and ground source heat pumps, hybrid heat pumps, and hydrogen boilers, in Table 5.7. The electricity and hydrogen tariffs have been given in Table 5.5. Renovation costs are based on figures by CE. Table 5.6 gives the insulation label improvement assumptions for households running all-electric heat pumps in the Netherlands in 2050. Investment cost assumptions for each device and calculations of household costs are as detailed under 'Model Inputs and Methodology'. For hybrid heat pumps, it is assumed that for each electricity tariff that applies to the electric heat pump component, the corresponding hydrogen tariff applies to the hydrogen boiler component, in Table 5.5. (For example, when the electricity tariff is 0.106 euros/kWh for the electric heat pump component of the hybrid heat pump, the hydrogen tariff for the hydrogen boiler component is 0.060 euros/kWh).

Effect of Energy Tariffs on Annual Cost per Household

Across households of all insulation labels in 2050, when energy tariffs are moderate/high (0.106-0.134 euros/kWh for electricity, 0.060-0.078 euros/kWh for hydrogen) hybrid heat pumps are the cheapest per household per year, while hydrogen boilers are cheaper per household annually than electric air and ground source heat pumps (except for high energy tariffs in households of insulation label F and G). Annual cost per household when running hydrogen boilers pumps is highest when energy tariffs are high and insulation quality is poor (households of insulation label E, F and G) as fuel costs (hydrogen cost) make up the majority of the annual costs per household for hydrogen boilers at all insulation levels. Electric air source heat pumps are the most expensive at high energy tariffs across all insulation levels. Improving household insulation levels could reduce annual costs per household for the hydrogen scenario as well, provided the annual energy savings are greater than the annual costs of household insulation.

Table 5.5 –Electricity and Hydrogen Tariff Inputs for 2050

Electricity Tariff (euros/kWh)	Hydrogen Tariffs (euros/kWh)
0.081	0.046
0.092	0.050
0.106	0.060
0.110	0.074
0.134	0.078

Table 5.6 – Insulation label improvement assumptions by 2050 for all-electric heat pumps (based on CE recommendations)

Insulation Label	Improved to
D	C
E	C
F	C
G	C

From Table 30, for all levels of household insulation, the increase in annual costs per household for electric heat pumps when going from low energy tariffs to high energy tariffs in 2050, is lower than the corresponding increase in annual costs when going from low to high tariffs for hydrogen boilers; the annual costs per household can be said to be more dependent on the energy tariffs (hydrogen tariffs) for households running hydrogen boilers, than the annual costs per households for electric heat pumps. This is further seen when considering that hydrogen fuel costs make up 86% – 97% of the annual costs per household for all insulation labels in 2050 (the fraction of annual hydrogen fuel costs increases with decreasing household insulation quality). By comparison, annual electricity costs make up 12% - 20% of the annual cost per household for air source heat pumps, and 7% - 18% of annual cost per household for ground source heat pumps.

For households of insulation label D, E, F and G in the hybrid scenario, 70% of the annual heat demand is assumed to be met by the hydrogen boiler component in 2050, compared to 40% of the demand being met by the hydrogen boiler in households of insulation label B and C, and 10% of the demand being met by the hydrogen boilers in households of label A.

Table 5.7 – Annual cost in euros per household for each scenario for each insulation label (2050)

Insulation Grade	Electricity Tariff (€/kWh)	Hydrogen Tariff (€/kWh)	ASHP Scenario	GSHP Scenario	Hybrid Scenario	Full Hydrogen Scenario
A	0.081	0.046	1542	1556	782	762
	0.092	0.050	1576	1584	814	806
	0.106	0.060	1619	1619	876	916
	0.110	0.074	1631	1629	939	1070
	0.134	0.078	1705	1690	990	1114
B	0.081	0.046	1651	1623	904	852
	0.092	0.050	1700	1660	946	904
	0.106	0.060	1762	1707	1035	1034
	0.110	0.074	1780	1721	1141	1215
	0.134	0.078	1886	1801	1199	1267
C	0.081	0.046	1783	1674	954	931
	0.092	0.050	1850	1718	1001	990
	0.106	0.060	1935	1774	1100	1137
	0.110	0.074	1959	1789	1215	1342
	0.134	0.078	2105	1885	1281	1401
D	0.081	0.046	2238	2129	1135	1010
	0.092	0.050	2304	2172	1197	1076
	0.106	0.060	2389	2228	1336	1240
	0.110	0.074	2414	2244	1515	1469
	0.134	0.078	2559	2339	1590	1535
E	0.081	0.046	2571	2463	1592	1552
	0.092	0.050	2638	2506	1697	1664
	0.106	0.060	2723	2562	1932	1946
	0.110	0.074	2748	2578	2230	2340
	0.134	0.078	2893	2673	2362	2453
F	0.081	0.046	2766	2657	1782	1777
	0.092	0.050	2833	2701	1905	1910
	0.106	0.060	2918	2757	2181	2240
	0.110	0.074	2942	2773	2528	2703
	0.134	0.078	3088	2868	2683	2835
G	0.081	0.046	2924	2815	1972	2003
	0.092	0.050	2991	2859	2114	2155
	0.106	0.060	3076	2914	2429	2535
	0.110	0.074	3100	2930	2826	3066
	0.134	0.078	3246	3026	3004	3218

The lower the household insulation quality, the smaller is the fraction of annual heat demand of 2050 (space heating, domestic hot water demand is assumed to be met by the boiler) that can be met by the electric heat pump component. The main advantage of the electric heat pump compared to the hydrogen boiler operation is that efficiencies greater than 1 can be achieved (when converting electricity to heat, as seen with the Coefficient of Performance). As the fraction of annual space heating demand met by the electric heat pump component reduces, so does the overall efficiency of the heat generation process of the hybrid heat pump, thus increasing the fuel expenses, therefore, the overall annual costs per household become more comparable to households running electric air and ground source heat pumps.

Furthermore, in households of insulation label A to D, the behaviour of hybrid heat pumps and the changes in annual cost per household when energy tariffs are increased in 2050, is closer to the behaviour of electric air and ground source heat pumps, as over 60% of the annual space heating demand is being met by the electric heat pump component (90% in households of insulation label A). In households running hydrogen boilers, the increase in annual cost per household when going from low to high energy tariffs is seen to be greater than the increase in annual costs per household when going from low to high energy tariffs in households running electric air and ground source heat pumps for all insulation labels.

For households of insulation label E to G, the heat pump component is assumed to meet only 30% of the annual space heating demand in 2050. For these households, the behaviour of hybrid heat pumps is closer to the behaviour of hydrogen boilers. When going from low to high energy tariffs, the observed increase in annual cost per household in greater in houses of poor insulation quality (insulation labels E, F and G) is greater than the increase in annual cost per household when going from low to high energy tariffs in households of insulation label A, B, C and D for hybrid heat pumps. The sensitivity of annual cost per household for terraced houses running hybrid heat pumps in to the energy tariffs in 2050 is given in Table 5.8. In the table, Average Sensitivity refers to the sensitivity over the whole range of electricity and hydrogen tariffs in 2050, as the lowest and highest values of the range has been used to calculate the change in cost over the entire range, for ΔP. The increase is assumed to be linear, and is done so in the model as well.

Table 5.8 – Sensitivity of Annual Cost per Household for Hybrid Heat Pumps to Energy Tariffs (2050)

Insulation Label	Percentage Change in Energy Tariffs (ΔP)	Percentage change in Annual Cost per Household (ΔC)	Average Sensitivity ($\frac{\Delta C}{\Delta P}$)
A	40	21	0.52
B	40	25	0.63
C	40	26	0.65
D	40	29	0.73
E	40	33	0.83
F	40	34	0.85
G	40	34	0.85

From Table 5.8, we see that for households of insulation label A running hybrid heat pumps in 2050, a 40% decrease in electricity and hydrogen tariffs causes a 20% decrease in annual costs per household, with 90% of annual space heating demand met by the electric heat pump component (sensitivity of 0.52 = 0.21/0.4). For households of insulation label C (with 60% of annual space heating demand being met by the electric heat pump), the annual costs decrease by 26% for a 40% decrease in energy tariffs (sensitivity of 0.65 = 0.26/0.4). In households with poor insulation quality (insulation label G) where 70% of annual space heating demand is met by the hydrogen boiler component, annual costs decrease by 34% for a 40% decrease in tariffs (sensitivity of 0.85 = 0.34/0.4) – as the fraction of annual space heating demand met by the electric heat pump component reduces, the sensitivity of annual cost per household to energy tariffs increases.

To see the effect of energy tariffs on annual household cost in 2050, the difference in annual cost under low and high energy tariffs needs to be known. In Table 5.5, it can be seen that there is a difference of 40% between the highest cost tariff input and the lowest cost tariff input for both electricity and hydrogen tariffs. For this decrease of 40% from high electricity tariffs to low electricity tariffs, annual cost per household falls by 10 – 12% for air source heat pumps, and 7 – 9% for ground source heat pumps. For the same decrease in hydrogen tariffs, annual costs per household decrease by 32 – 37% for hydrogen boilers – costs when running hydrogen boilers are more sensitive to energy prices, when compared to the situation when running electric air and ground source heat pumps – for hydrogen boilers, the main uncertainty is in the energy tariffs (price of hydrogen in 2050).

In the thesis report "Predicting energy consumption and savings in the housing stock" by Dasa Majcen, it was found that the actual consumption in houses with insulation labels A and B was greater than the theoretically calculated value by 10% to 25%, whereas for houses with insulation label C and D, the theoretically calculated consumption was greater than the actual value by 6% - 18%. For houses of insulation labels E, F and G, the theoretical consumption was higher than the actual consumption by 31% to 50%. According to the report, households with lower quality insulation utilize heating in very specific patterns to minimize household bills, heating up individual rooms intermittently, and leaving unoccupied rooms unheated. [35]

Following the observations in the thesis by Dasa Majcen, it is likely that the energy consumption per home is overestimated for dwellings with insulation grades C to G by the calculation method used in the present study, for hybrid heat pumps and hydrogen boilers. For dwellings with lower quality insulation, spaces are generally heated in a more strategic manner by the occupants in order to reduce heat demand. Dwellings are heated only during certain hours of the day, and the entire dwelling is not heated all at once, thereby reducing the total area to be heated at any given moment, and reducing the total number of heating hours.

For dwellings running electric air and ground source heat pumps in 2050, it is assumed that households of insulation label D to G will undergo renovations to improve their insulation label to C in the present study. The theoretically calculated annual costs per household were found to have been overestimated by 6% compared to actual annual costs per household in [35], so it is likely that the annual costs per household have been slightly overestimated for houses of insulation label C and lower when running electric air or ground source heat pumps. The reasoning in [35] applies only to space heating demand; domestic hot water demand remains fairly constant throughout the year, and has been assumed as such in the present study as well.

For dwellings with better insulation levels (label A and B), the calculated energy consumption for 2050 in the present study might be an underestimate. According to [35], the theoretically calculated annual cost per household was found to have been underestimated by 8% for households of insulation label B, and 25% for households with insulation label A, compared to actual annual household heating costs. Occupants of dwellings with better insulation tend to maximise their perceived comfort, and the heating systems in many large, detached houses with good insulation tend to be central heating systems, or underfloor heating coils, which maximise the heated area and increase energy consumption over the theoretically calculated energy consumption value. By this reasoning, it is likely that the annual costs for houses of insulation grade A and B have been underestimated for all devices.

Determining the exact amount of heat consumed per household in 2050 would require an experimental approach similar to the one employed in [35] but it is not an insignificant point – electric heat pumps would require continuous operation to maximise their performance, but hybrid heat pumps can be fired rapidly using the boiler function, same as hydrogen boilers. The time of use pattern can significantly alter annual costs per household. The cost breakup for each device for terraced houses, excluding the cost of renovations to further improve the household insulation label is shown in the Figs. 1 and 2, for households of insulation labels A and D respectively, and for moderate electricity and hydrogen tariffs.

The method of calculating annual space heating and hot water demand per household for 2050 in the Netherlands used in the present study is not a time-dependent model – energy supply and demand are not matched for every time interval, the annual space heating and hot water demands are calculated directly from the length of the heating season, and the average daily difference in temperature between indoors and outdoors. As such, the amount of electricity storage energy required in 2050 cannot be calculated. However, the levelized system cost of electricity provided in the studies used as inputs for the present study (studies [7], [8], [9] and [11]) were calculated including the levelized cost of storing electricity (majority from battery storage). The electricity tariffs selected for the present study can be said to include the cost of storage as well, as they have been taken from the mentioned studies.

The amount of hydrogen storage required, and the effect of hydrogen storage costs on the final hydrogen tariff also cannot be calculated this way in the present study. Hydrogen storage costs for 2050 are also highly uncertain, given that large scale hydrogen storage does not exist yet. According to DNV-GL's report "Hydrogen in the Electricity Value Chain" [59] the projected levelized cost of hydrogen storage for 2050 was found to be between 0.3 euros/Kg (7.5 euros/MWh) of hydrogen for aquifer storage, to 1.7 euros/Kg (42.5 euros/MWh) of hydrogen for cryogenic vessel storage. These values are not very different from the hydrogen production costs chosen as price inputs in the present study, and as storage costs are even more uncertain than production costs of hydrogen, the cost of hydrogen storage in 2050 has not been explicitly included in the present study. However, as the levelized storage cost estimates for 2050 [59] are of comparable value to the hydrogen tariffs in the present study, it is unlikely, based on the cost figures provided in [59], that including hydrogen storage costs will add a large amount to the overall cost of the hydrogen or hybrid pathways, and has been ignored in the present study. Table 5.9 gives the annual cost, in euros per household, of improving household insulation levels for all types of dwellings in the all-electric heat pump options in 2050. Table 5.10 gives the summary of the annual costs per household for terraced houses in the Netherlands in 2050.

Table 5.9 – Annual Cost in euros per Household of Improving Household Insulation Levels for all dwelling types in the all-electric heat pump options in 2050

Type of Dwelling	Insulation Improvement Step	D to C	E to C	F to C	G to C
Terraced Houses	Annual Cost per Household (Euros)	454	788	983	1141
Low-rise Flats	Annual Cost per Household (Euros)	239	416	518	602
High-rise Flats	Annual Cost per Household (Euros)	341	591	737	856
Semi-detached Houses	Annual Cost per Household (Euros)	497	862	1075	1248
Detached Houses	Annual Cost per Household (Euros)	560	973	1213	1408

Table 5.10 – Summary of Annual Costs per Household (Terraced Houses in 2050)

Insulation Grade	Summary
A	Hybrid heat pumps – lowest annual cost per household per year for moderate/high energy tariffs (0.106-0.134 euros/kWh for electricity, 0.046-0.060 euros/kWh for hydrogen). Hydrogen boilers – lowest annual cost per household per year under low energy tariffs (0.046-0.050 euros/kWh for hydrogen). Electric ground source heat pumps – most expensive per household under low electricity tariffs (0.081-0.092 euros/kWh). Air source heat pumps are the most expensive per household under high energy tariffs. Hydrogen boilers and hybrid heat pumps - cheaper annually than electric air and ground source heat pumps for all energy tariffs.
B	Hybrid heat pumps – lowest annual cost per household per year for high energy tariffs (0.110-0.134 euros/kWh for electricity, 0.074-0.078 euros/kWh for hydrogen). Hydrogen boilers – lowest annual cost per household per year under low/moderate energy tariffs (0.046-0.060 euros/kWh for hydrogen). Hydrogen boilers and hybrid heat pumps - cheaper annually than electric air and ground source heat pumps for all energy tariffs. Air source heat pumps are the most expensive per household under all energy tariffs.
C	Hybrid heat pumps – lowest annual cost per household per year for moderate/high energy tariffs (0.106-0.134 euros/kWh for electricity, 0.046-0.060 euros/kWh for hydrogen). Hydrogen boilers – lowest annual cost per household per year under low energy tariffs (0.046-0.050 euros/kWh for hydrogen). Air source heat pumps are the most expensive per household under all energy tariffs. Hydrogen boilers and hybrid heat pumps - cheaper annually than electric air and ground source heat pumps for all energy tariffs.
D	Hybrid heat pumps – lowest annual cost per household per year for high energy tariffs (0.110-0.134 euros/kWh for electricity, 0.074-0.078 euros/kWh for hydrogen). Hydrogen boilers – lowest annual cost per household per year under low/moderate energy tariffs (0.046-0.060 euros/kWh for hydrogen). Hydrogen boilers and hybrid heat pumps - cheaper annually than electric air and ground source heat pumps for all energy tariffs. Air source heat pumps are the most expensive per household under all energy tariffs.
E	Hybrid heat pumps – lowest annual cost per household per year for moderate/high energy tariffs (0.106-0.134 euros/kWh for electricity, 0.046-0.060 euros/kWh for hydrogen). Hydrogen boilers – lowest annual cost per household per year under low energy tariffs (0.046-0.050 euros/kWh for hydrogen). Air source heat pumps are the most expensive per household under all energy tariffs. Hydrogen boilers and hybrid heat pumps - cheaper annually than electric ground source heat pumps for all energy tariffs.
F	Hybrid heat pumps – lowest annual cost per household per year for all energy tariffs except when electricity tariff = 0.081 euros/kWh and hydrogen tariffs = 0.046 euros/kWh. Hydrogen boilers are the cheapest at these tariffs. Electric air source heat pumps are the most expensive per household for all energy tariffs. Hydrogen boilers are cheaper than ground source heat pumps for low/moderate tariffs (0.081-0.106 euros/kWh electricity, 0.046-0.060 euros/kWh hydrogen).
G	Hybrid heat pumps – lowest annual cost per household per year under low/moderate energy tariffs (0.081-0.106 euros/kWh for electricity, and 0.046-0.060 euros/kWh for hydrogen). Electric air source heat pumps – cheapest per household under high energy tariffs (0.110-0.134 euros/kWh for electricity, 0.074-0.078 euros/kWh for hydrogen. Electric air source heat pumps – most expensive per household for all energy tariffs.

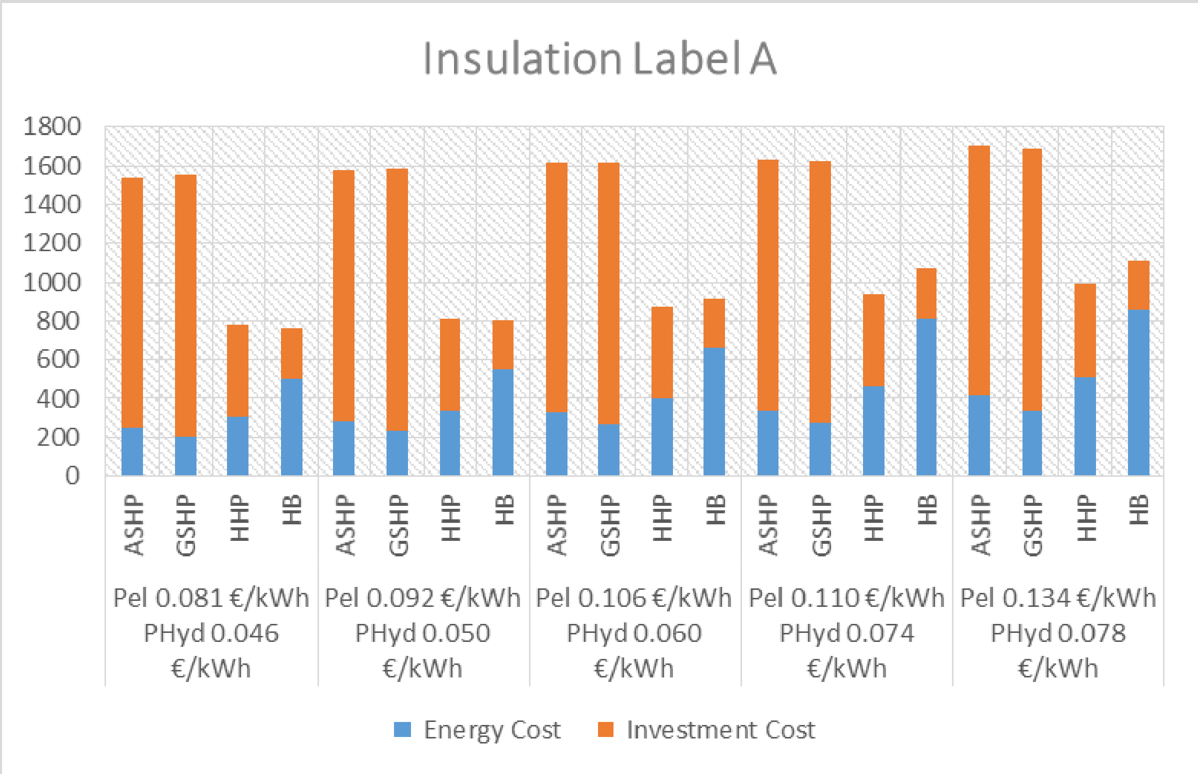


Fig. 5.1 – Comparison of Annual Cost per Household for Each Decarbonisation Technology, in euros, for households of insulation label A in 2050

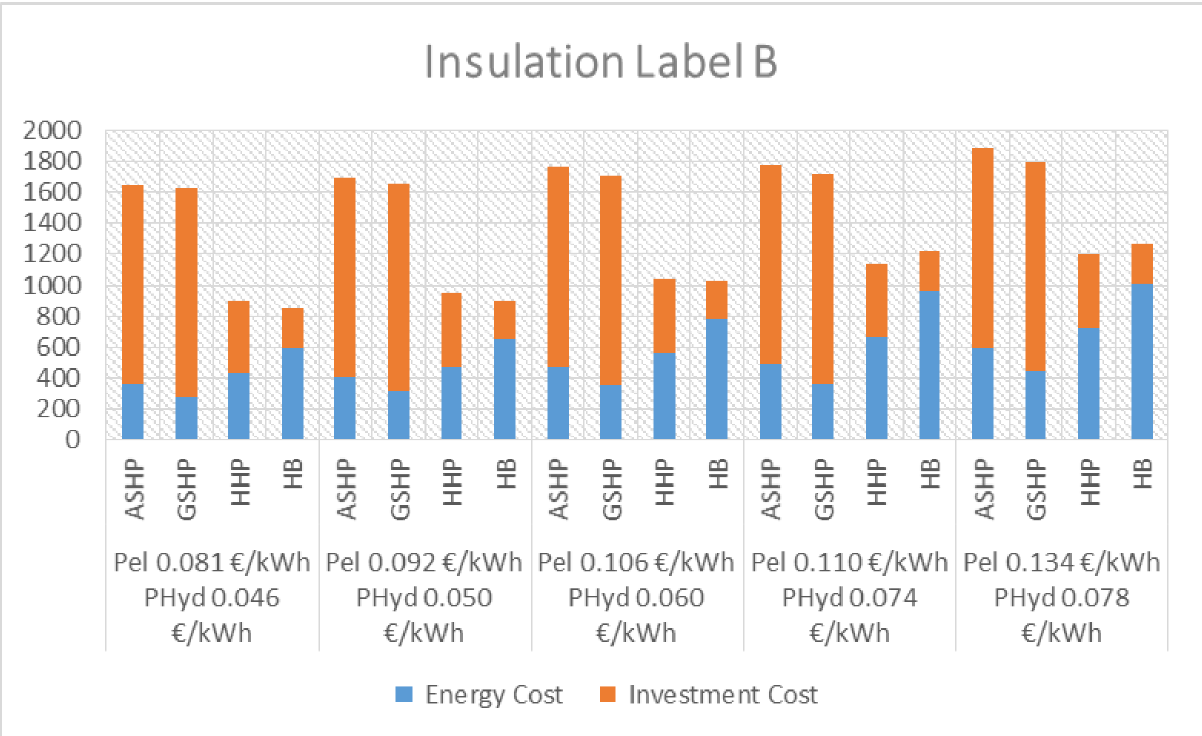


Fig. 5.2 – Comparison of Annual Cost per Household for Each Decarbonisation Technology, in euros, for households of insulation label B in 2050

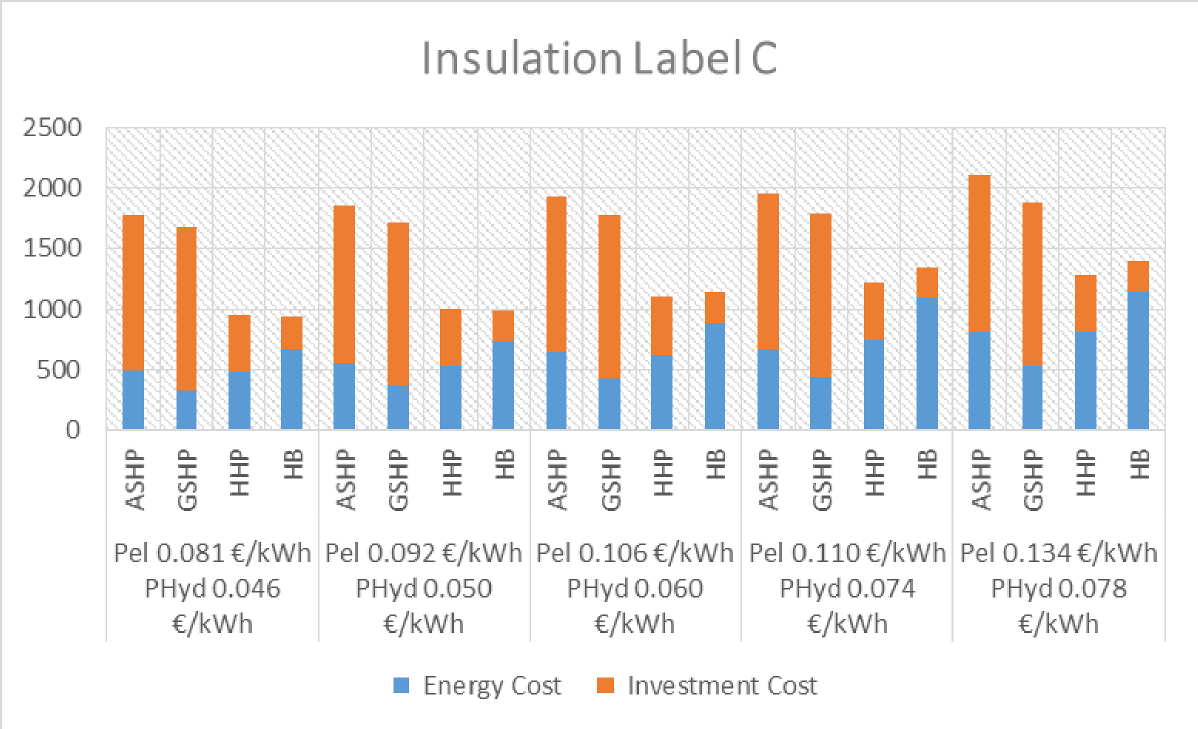


Fig. 5.3 – Comparison of Annual Cost per Household for Each Decarbonisation Technology, in euros, for households of insulation label C in 2050

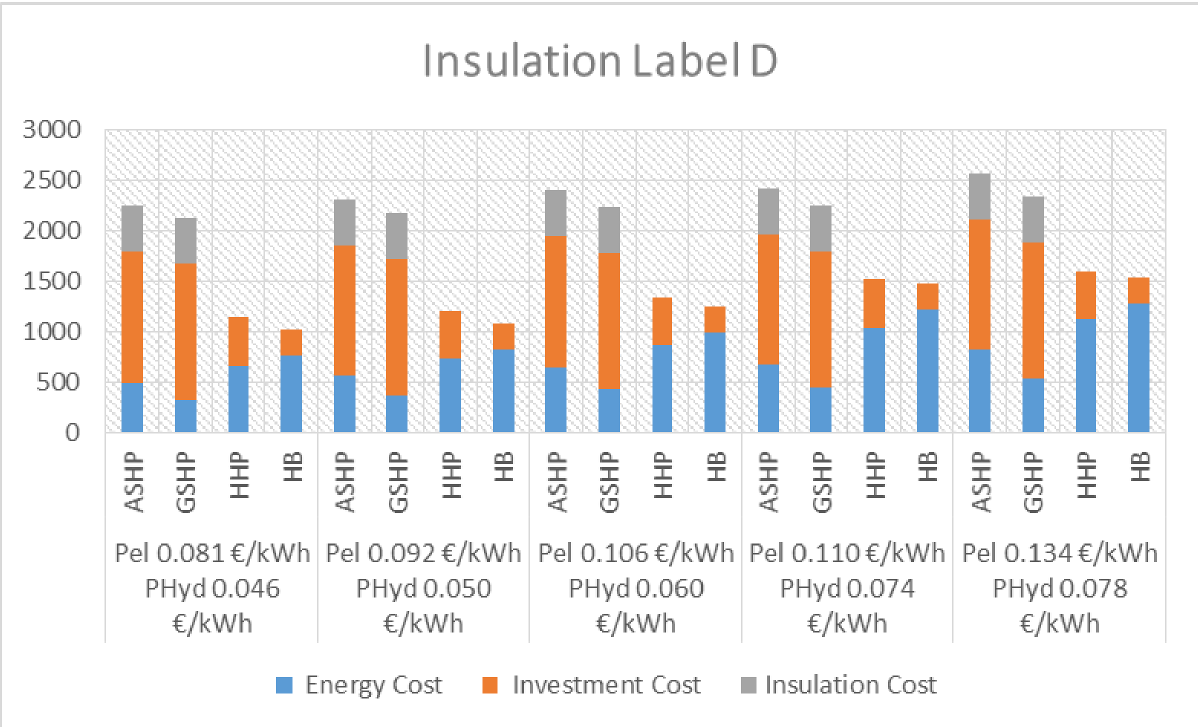


Fig. 5.4 – Comparison of Annual Cost per Household for Each Decarbonisation Technology, in euros, for households of insulation label D in 2050

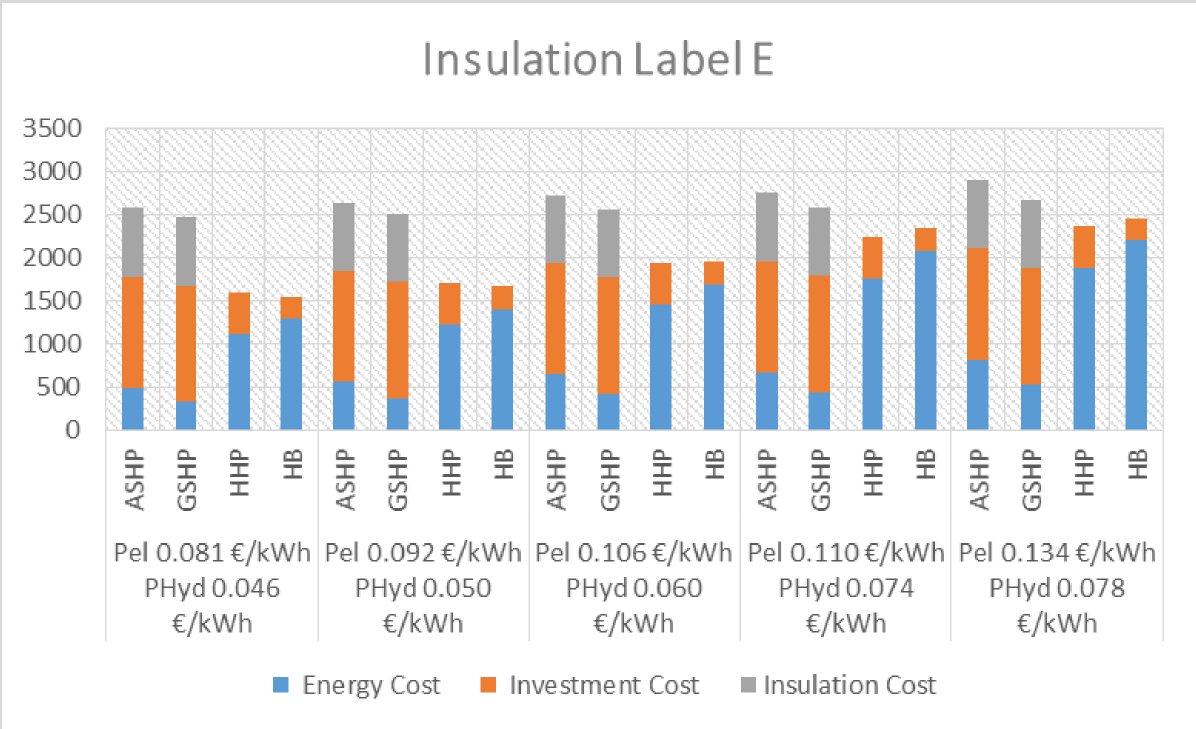


Fig. 5.5 – Comparison of Annual Cost per Household for Each Decarbonisation Technology, in euros, for households of insulation label E in 2050

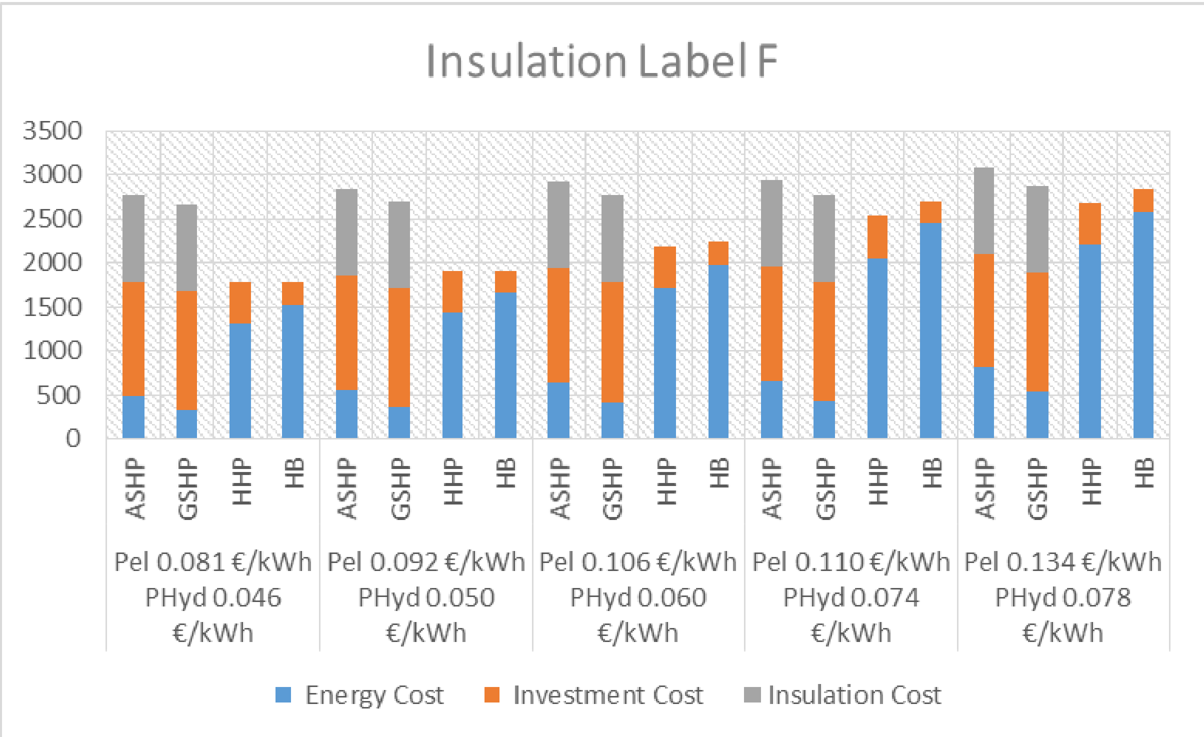


Fig. 5.6 – Comparison of Annual Cost per Household for Each Decarbonisation Technology, in euros, for households of insulation label F in 2050

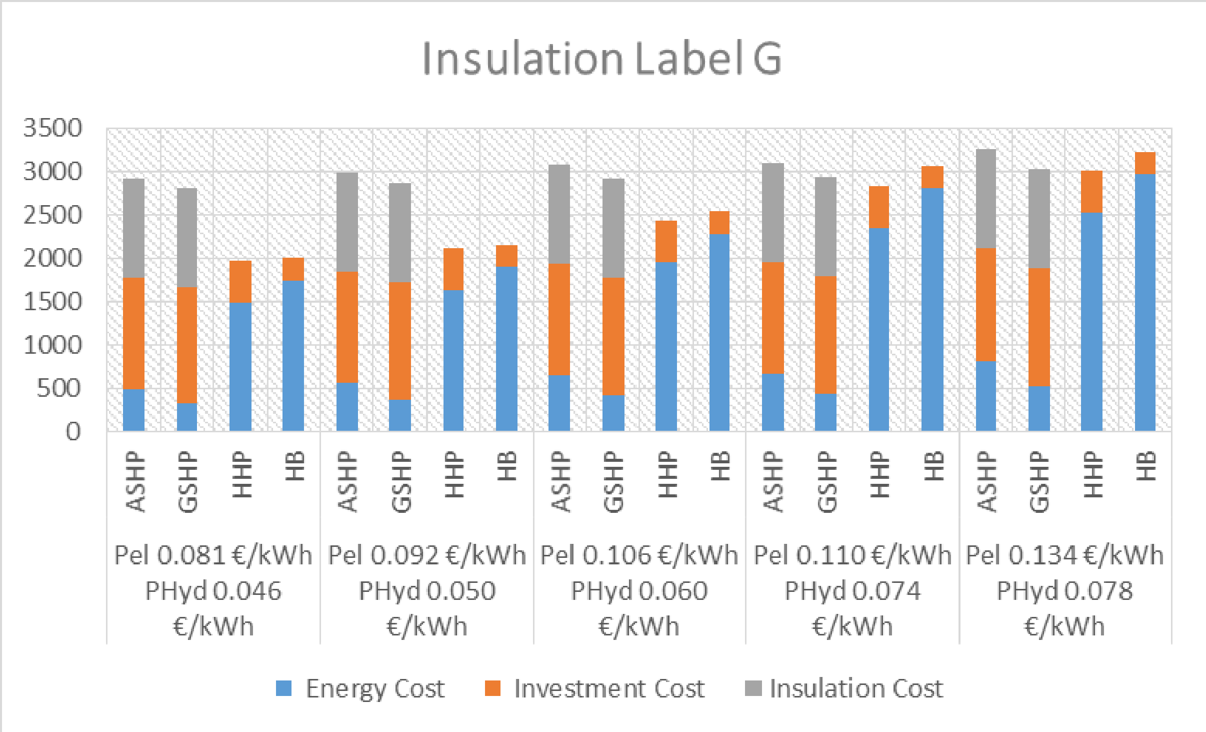


Fig. 5.7 – Comparison of Annual Cost per Household for Each Decarbonisation Technology, in euros, for households of insulation label G in 2050

Figures 5.1 – 5.7 compare the annual costs per household for households of each insulation label A to G in terms of annual investment costs (device annual investment cost, device annual maintenance cost, and cost of investment in low temperature radiators), and annual energy costs, for 2050. Investment costs include the costs of renovations to improve household insulation levels for houses with electric air and ground source heat pumps – costs for households of insulation label D, E, F and G include renovation costs. In the figures, Pel refers to the electricity tariff, PHyd to the hydrogen tariff (both in euros/kWh), ASHP refers to air source heat pumps, GSHP refers to ground source heat pumps, HHP refers to hybrid heat pumps, and HB refers to hydrogen boilers. The cost of disconnecting from the gas grid and the cost of strengthening household electricity grid connection for the electric heat pump scenarios has been included as well. Each figure compares the annual costs of the devices for all five energy tariffs from low to high. In each figure, ‘Insulation Cost’ refers to the cost of renovations to improve insulation label. Renovation costs make up 20-25% of the annual costs per household in dwellings of label D that have been renovated to label C in 2050. In households of label G, renovating to label C makes up 45% of the annual cost per household, for terraced houses in 2050. For electric air and ground source heat pumps, investment costs are the majority of annual costs per household, for hydrogen boilers, fuel costs are the majority of the annual cost per household in 2050.

Table 5.11 – Comparison of Investment Costs of Each Decarbonisation Technology per Household for Terraced Houses in 2050

Decarbonization Technology	Annual Device Capital Investment Costs	Annual Secondary Investment Costs
Air Source Heat Pumps	890	276
Ground Source Heat Pumps	981	276
Hybrid Heat Pumps	337	0
Hydrogen Boilers	126	0

In Table 5.11, the annual investment costs for electric air and ground source heat pumps, hybrid heat pumps and hydrogen boilers have been given for terraced houses in the Netherlands in 2050. Device capital investment costs are the cost of purchasing and installing the decarbonisation device itself. Secondary investment costs include the cost of disconnecting from the gas grid, the cost of strengthening household electrical grid connection and the cost of purchasing low temperature radiators, all for electric air and ground source heat pumps. Operation and maintenance (O&M) costs fall under operational costs and are not included in Table 5.11. All capital costs have been annuitized as detailed in the 'Model Inputs and Methodology' chapter.

From the table (and from Figures 5.1 – 5.7), it can be seen that electric air and ground source heat pumps have significantly higher capital investment costs in 2050 than hybrid heat pumps and hydrogen boilers; they are the dominant annual costs in households running air and ground source heat pumps. Despite the theoretically higher energy performance of air and ground source heat pumps (electric heat pumps have the lowest energy costs amongst heat pumps, hybrid heat pumps, and hydrogen boilers), the high annual investment costs lead to electric air and ground source heat pumps being more expensive than hybrid heat pumps and hydrogen boilers in almost all cases in 2050.

5.3 Sensitivity Analysis for Investment Costs of Electric Heat Pumps

The inputs used in the present study to calculate the annual cost per household in 2050 come from a number of sources and have large variations. The calculated levelized system cost of a 100% renewable energy system for a Europe-wide electricity grid vary from 57 euros/MWh of electricity, to 110 euros/MWh. The hydrogen production costs for 2050 from several reports varies from 20 euros/MWh to 75 euros/MWh. These ranges of cost have led to a wide range in the selected input tariffs for electricity and hydrogen for the Netherlands in 2050, leading to large differences in annual energy cost.

The investment costs for electric heat pumps given in the chapter 'Model Inputs and Methodology' vary widely as well, as do the estimates for the reduction in investment costs of each device up to 2050. For air source heat pumps, the lower limit of the device investment cost given in literature from various sources as detailed in section 3.9.1 of this report - 'All-Electric Heat Pumps' ranges from 5000 euros/device to 6500 euros/device. The upper limit of device capital investment costs for air source heat pumps ranges from 10000 euros/device to 14500 euros/device.

In the previous section, the annual cost per household for electric air source heat pumps was given taking device capital investment cost of air source heat pumps in the upper region of the device capital investment cost estimates (10000 – 14500 euros per device), and assuming that electric air and ground source heat pumps would both become 17% cheaper by 2050 in the Netherlands, the lower end of the cost reduction estimates from various sources. The upper end of the cost reduction estimates by 2050 for air source heat pumps is 33%, for ground source heat pumps, the upper end of the cost reduction estimates is 27%.

As seen in the previous section, annual device capital costs are the dominant annual investment costs in households running air and ground source heat pumps, followed by renovations to improve household insulation levels. Secondary capital investments such as the cost of low temperature radiators by 2050 carry some uncertainty according to various sources, as detailed by Bekhuis in [10]. The effect of these uncertainties on the annual cost per household for electric air and ground source heat pumps is investigated in the following sections.

5.3.1. Effect of Device Capital Investment Cost Reductions – Electric Heat Pumps

For ground source heat pumps, the lower limit of the device investment cost given in literature from various sources ranges from 8500 euros/device to 12000 euros/device. The upper limit of device capital investment costs for air source heat pumps ranges from 12000 euros/device to 16500 euros/device. In '5.2 - Annual Costs per Household Including Renovation Cost to Improve Household Insulation', it was seen that the annual costs per household are less sensitive to the energy tariffs in 2050 for air and ground source heat pumps than for hydrogen boilers.

For air and ground source heat pumps, the effect of device investment cost on the annual cost per household can be studied by comparing the annual costs of electric heat pumps per household in Table 5.7 with the annual cost per household when taking investment cost reductions in the lower range of estimates from literature, for both air and ground source heat pumps. The investment cost assumptions for 2050 have been given in Table 5.12. In the table, ASHP refers to air source heat pumps, GSHP to ground source heat pumps. Costs are exclusive of VAT.

The costs of hybrid heat pumps in the present study are assumed to be 30% lower in 2050 compared to present costs, based on various sources, without the wide range of estimates as present with electric heat pumps, so they are not investigated here. Hydrogen boilers 2050 are assumed to be similar in cost to present day gas boilers in the present study, with investment costs making up less than 20% of annual cost per household and are also not investigated here. Table 5.14 compares the total annual cost per household for air and ground source heat pumps assuming a 17% reduction in device capital investment (8473 euros) cost by 2050 with respect to current costs, with the total annual cost per household assuming a 33% reduction (6839 euros) in device capital investment cost for air source heat pumps, and a reduction of 27 % for ground source heat pumps by 2050.

Table 5.12 – Investment Cost Assumptions for Electric Heat Pumps in 2050 for Terraced Houses

Heating Technology	Prior Cost Reduction Assumptions by 2050 Compared to Current Costs	New Cost Reduction Assumptions by 2050 Compared to Current Costs	New Device Capital Investment Cost for 2050 (euros/Device)
ASHP	17%	33%	6839
GSHP	17%	27%	8669

From Table 5.14, for air source heat pumps, when assuming that device capital investment cost reduces by 33% (i.e. when cost is 6839 euros) by 2050 with respect to current prices, the annual cost per household drops by 169 euros/year. This causes the total annual cost per household for air source heat pumps to drop by 10 - 11% (0.10 – 0.11) in 2050 for households of insulation label A, and 4 - 5% (0.04 – 0.05) for households of insulation label G that have been renovated to insulation label C. When compared to the annual costs per household when assuming a 17% decrease in device capital investment cost for air source heat pumps (8473 euros/device), the investment cost inputs from Table 5.12 are 19% lower (6839 euros is 19% less than 8473 euros, the previous investment cost assumption for air source heat pumps).

The annual energy costs per household increase with decreasing quality of household insulation, and increasing energy tariff. This causes the annual cost fraction of the device capital investment cost to decrease with decreasing household insulation quality and energy tariffs for air and ground source heat pumps, (and, in fact, for all devices considered in the present study). As the annual cost fraction of device capital investment cost decreases, so does the sensitivity of the total annual cost per household to the device capital investment cost in 2050.

For air source heat pumps in households with insulation label A, a 19% fall in device capital investment cost leads to a 10 – 11% (0.10 – 0.11) fall in total annual cost per household, and a 4 - 5% (0.04 – 0.05) fall in total annual cost per household when air source heat pumps are used in households with insulation label G renovated to label C in 2050. The sensitivity of the total annual cost per household for each insulation label to the device capital investment cost is given in Table 5.13.

For ground source heat pumps, when assuming that device capital investment cost reduces by 27% by 2050 (when cost is 8669 euros) with respect to current prices, the annual cost per household drops by 117 euros/year. This causes the total annual cost per household for ground source heat pumps to drop by 7 - 7.5% (0.07 – 0.08) for households of insulation label A, and 4 - 5% (0.04 – 0.05) for households of insulation label G that have been renovated to insulation label C.

When compared to the annual costs per household in 2050 when assuming a 17% decrease in device capital investment cost for air source heat pumps (9856 euros/device), the investment cost inputs for Table 5.12 are 12% lower (8669 euros is 12% less than 9856 euros, the previous investment cost assumption for ground source heat pumps). Cross-sensitivity with electricity tariffs was not included, as within the same insulation label, sensitivity varied by less than 10%.

Taking the variation of output with respect to the variation of input as the metric to measure sensitivity, given below –

$$Sensitivity = \frac{\Delta Output\ (percentage\ change\ in\ 2050)}{\Delta Input\ (percentage\ change\ in\ 2050)}$$

Where $\Delta Output$ is the change in output value (in this case, total annual cost per household in 2050) and $\Delta Input$ is the change in input value (device capital investment cost in 2050). For households of insulation label A using air source heat pumps, the sensitivity of the total annual cost per household to the device capital investment cost is 0.58 ($\Delta Output/\ \Delta Input$ = 0.11/0.19 = 0.58). The sensitivity of ground source heat pumps for households of insulation label A is 0.67 ($\Delta Output/\ \Delta Input$ = 0.08/0.12 = 0.67). For households of insulation label G, the sensitivity to device capital investment cost is 0.27 ($\Delta Output/\ \Delta Input$ = 0.05/0.19 = 0.26) and for ground source heat pumps, it is 0.32 ($\Delta Output/\ \Delta Input$ = 0.04/0.12 = 0.32).

Table 5.13 – Sensitivity of Annual Cost per Household for Electric Heat Pumps to Device Capital Investment Cost (2050)

Insulation Label	% Reduction in Device Capital Investment Cost (ΔP)		% Reduction in Annual Cost per Household (ΔC)		Sensitivity ($\frac{\Delta C}{\Delta P}$)	
	ASHP	GSHP	ASHP	GSHP	ASHP	GSHP
A	19	12	11	8	0.58	0.67
B	19	12	9	6.5	0.47	0.54
C	19	12	8	6.2	0.42	0.52
D	19	12	7	5	0.35	0.42
E	19	12	6	4.4	0.31	0.36
F	19	12	5	4	0.27	0.34
G	19	12	5	4	0.27	0.32

Annual costs per household are seen to be more sensitive to device capital investment costs for ground source heat pumps than for air source heat pumps in 2050 – ground source heat pumps have lower annual energy costs, but higher investment costs than air source heat pumps. By comparison, the sensitivity of total annual costs to electricity tariffs using the same procedure is 0.25 when taking electricity tariffs to ranges from 0.081 euros/kWh to 0.134 euros/kWh (40% decrease when going from high to low tariffs), showing that annual costs per household in 2050 are highly sensitive to device capital investment costs for air and ground source heat pumps.

Table 5.14 – Comparison of Annual Cost in Euros per Household for Air and Ground Source Heat Pumps for Each Insulation Label (2050)

Insulation Grade	Electricity Tariff (€/kWh)	Hydrogen Tariff (€/kWh)	ASHP Scenario (17% cost reduction)	ASHP Scenario (33% cost reduction)	GSHP Scenario (17% cost reduction)	GSHP Scenario (27% cost reduction)
A	0.081	0.046	1542	1373	1556	1439
	0.092	0.050	1576	1407	1584	1467
	0.106	0.060	1619	1450	1619	1502
	0.110	0.074	1631	1462	1629	1512
	0.134	0.078	1705	1537	1690	1573
B	0.081	0.046	1651	1482	1623	1506
	0.092	0.050	1700	1531	1660	1543
	0.106	0.060	1762	1593	1707	1590
	0.110	0.074	1780	1611	1721	1603
	0.134	0.078	1886	1717	1801	1684
C	0.081	0.046	1783	1614	1674	1557
	0.092	0.050	1850	1681	1718	1601
	0.106	0.060	1935	1766	1774	1656
	0.110	0.074	1959	1790	1789	1672
	0.134	0.078	2105	1936	1885	1768
D	0.081	0.046	2238	2069	2129	2012
	0.092	0.050	2304	2135	2172	2055
	0.106	0.060	2389	2220	2228	2111
	0.110	0.074	2414	2245	2244	2127
	0.134	0.078	2559	2390	2339	2222
E	0.081	0.046	2571	2402	2463	2345
	0.092	0.050	2638	2469	2506	2389
	0.106	0.060	2723	2554	2562	2445
	0.110	0.074	2748	2579	2578	2461
	0.134	0.078	2893	2724	2673	2556
F	0.081	0.046	2766	2597	2657	2540
	0.092	0.050	2833	2664	2701	2584
	0.106	0.060	2918	2749	2757	2640
	0.110	0.074	2942	2773	2773	2655
	0.134	0.078	3088	2919	2868	2751
G	0.081	0.046	2924	2755	2815	2698
	0.092	0.050	2991	2822	2859	2742
	0.106	0.060	3076	2907	2914	2797
	0.110	0.074	3100	2931	2930	2813
	0.134	0.078	3246	3077	3026	2909

5.3.2 Effect of Cost Reductions for Household Insulation Renovations and Low Temperature Radiators on Annual Cost per Household – Electric Heat Pumps

In Bekhuis' thesis [10], cost reduction assumptions for renovations to improve household insulation was taken as 0.75 by the year 2040 for high level insulation improvements, while that of low temperature radiators was taken as 0.8 by the year 2040. These costs are assumed to be considered in the present study only for the all-electric air and ground source heat pumps options, and are counted as part of the overall investment cost per household when purchasing electric heat pumps.

As renovation investment costs also make a large part of the annual costs for heat pumps in 2050, the annual cost per household for each insulation label has also been calculated when taking these investment cost reductions as well. For this section, it is assumed that investment cost reduction factor for low temperature radiators is 0.8 by the year 2050 in the Netherlands, and the cost reduction factor of household renovations for the year 2050 has been taken as 0.75, both based on figures provided in [10]. Device capital investment costs are assumed to drop by 33% for air source heat pumps by 2050, while those of ground source heat pumps are assumed to drop by 27% by 2050 in the Netherlands, same as in Table 5.11. The assumptions have been summarized in Table 5.15. Costs are exclusive of VAT.

Table 5.15 – Cost Reduction Assumptions for Renovations Costs and Low Temperature Radiators for 2050 in the Netherlands

Decarbonisation technology	Device Capital Investment Cost (euros)	Renovation Cost Reduction Factor Compared to Current Prices (2050)	Radiator Cost Reduction Factor Compared to Current Prices (2050)
Air source Heat Pumps	6839 (33% reduction from present-day costs)	0.75	0.8
Ground Source Heat Pumps	8669 (27% reduction from present-day costs)	0.75	0.8

Table 5.16 compares the annual cost per household for air and ground source heat pumps for each insulation label taking into account cost reduction of household renovation and radiators as given in Table 5.13, in 2050. In Table 5.14, households of insulation label A, B and C will not see any effects from renovation cost reductions, as these dwellings were assumed to not require renovation by CE recommendations, while using electric heat pumps. For these households, the effect of reducing radiator investments alone can be studied.

Reducing the investment cost of low temperature radiators by 20% (cost reduction factor 0.8) causes the total annual cost per household to fall by 38 euros per year for households of all insulation labels in 2050, as the cost of radiators is not dependent on the household insulation level. For households of insulation label A, this causes total annual costs per household to fall by 2.5 - 2.8%, from high electricity tariffs, to low electricity tariffs, in Table 5.14. $\Delta Output/\ \Delta Input$ = 0.028/0.2 = 0.14. The sensitivity of annual cost per household to the cost of low temperature radiators is not very high for air source heat pumps when compared to the sensitivity to device capital investment costs, even for households with insulation label A. The sensitivity decreases with decreasing household insulation quality. The sensitivity for ground source heat pumps is also comparatively low, (compared to device investment costs) at 0.13.

Households of insulation label G that have been renovated to insulation label C have the highest annual investment costs for household renovation, consequently, they are the most sensitive to the cost of home renovations compared to households that have lower renovation costs. Reducing renovation costs by 25% for 2050 (cost reduction factor 0.75) decreases total annual cost per household by 10% (0.10) in 2050, for households of insulation label G (renovated to label C and not including the 38 euro/year decrease from reducing investment costs of low temperature radiators) running air source heat pumps. $\Delta Output/\ \Delta Input$ = 0.10/0.25 = 0.40. For households of insulation label D renovated to label C and running air source heat pumps, the sensitivity to renovation cost is 0.20 ($\Delta Output/\ \Delta Input$ =

0.05/0.25). For ground source heat pumps in households of insulation label G (renovated to label C and not including the 38 euro/year decrease from reducing investment costs of low temperature radiators), the sensitivity to renovation costs is 0.40 ($\Delta Output / \Delta Input$ = 0.10/0.25), for households of insulation label D (renovated to label C), the sensitivity to renovation costs is 0.21 ($\Delta Output / \Delta Input$ = 0.05/0.25).

Table 5.16 – Comparison of Annual Cost in Euros per Household for Air and Ground Source Heat Pumps for Each Insulation Label Taking into Account Cost Reduction of Household Renovation and Radiators (2050)

Insulation Grade	Electricity Tariff (€/kWh)	Hydrogen Tariff (€/kWh)	ASHP (33% cost reduction)	ASHP (33% cost reduction and reduced cost of radiators and insulation)	GSHP (27% cost reduction)	GSHP (27% cost reduction and reduced cost of radiators and insulation)
A	0.081	0.046	1373	1335	1439	1401
	0.092	0.050	1407	1369	1467	1429
	0.106	0.060	1450	1412	1502	1464
	0.110	0.074	1462	1424	1512	1474
	0.134	0.078	1537	1499	1573	1535
B	0.081	0.046	1482	1444	1506	1468
	0.092	0.050	1531	1493	1543	1505
	0.106	0.060	1593	1555	1590	1552
	0.110	0.074	1611	1573	1603	1565
	0.134	0.078	1717	1679	1684	1646
C	0.081	0.046	1614	1576	1557	1519
	0.092	0.050	1681	1643	1601	1563
	0.106	0.060	1766	1728	1656	1618
	0.110	0.074	1790	1752	1672	1634
	0.134	0.078	1936	1898	1768	1730
D	0.081	0.046	2069	1917	2012	1860
	0.092	0.050	2135	1984	2055	1904
	0.106	0.060	2220	2069	2111	1959
	0.110	0.074	2245	2093	2127	1975
	0.134	0.078	2390	2239	2222	2071
E	0.081	0.046	2402	2167	2345	2110
	0.092	0.050	2469	2234	2389	2154
	0.106	0.060	2554	2319	2445	2210
	0.110	0.074	2579	2343	2461	2226
	0.134	0.078	2724	2489	2556	2321
F	0.081	0.046	2597	2313	2540	2256
	0.092	0.050	2664	2380	2584	2300
	0.106	0.060	2749	2465	2640	2356
	0.110	0.074	2773	2490	2655	2372
	0.134	0.078	2919	2635	2751	2467
G	0.081	0.046	2755	2432	2698	2375
	0.092	0.050	2822	2499	2742	2418
	0.106	0.060	2907	2584	2797	2474
	0.110	0.074	2931	2608	2813	2490
	0.134	0.078	3077	2753	2909	2585

Table 5.17 – Sensitivity of Annual Cost per Household for Electric Heat Pumps to Household Renovation Costs (2050)

Insulation Label	**% Reduction in Cost of Renovation by 2050 (ΔP)**	**% Reduction in Annual Cost per Household (ΔC)**		**Sensitivity ($\frac{\Delta C}{\Delta P}$)**	
		ASHP	GSHP	ASHP	GSHP
D	25	5	5	0.20	0.21
E	25	7	8	0.29	0.32
F	25	8	9	0.32	0.36
G	25	10	10	0.40	0.40

5.4 Summary

1) Total annual costs per household in 2050 are dependent on the annual investment (annual device capital investment cost, annual cost of renovations, and annual cost of low temperature radiators) and device annual maintenance cost and the annual energy cost per household. Annual energy costs are dependent on the electricity and hydrogen tariffs, the annual heat demand per household, and the heating device used. Annual heat demand strongly depends on level of household insulation, building geometry and difference between indoor and outdoor temperatures.
2) The annual cost per household in 2050 for houses using hydrogen boilers is more sensitive to the energy tariffs than those of air source, ground source, and hybrid heat pumps - fuel expenses make up a greater fraction of annual cost per household when using hydrogen boilers as compared to the other technologies.
3) Ground source heat pumps are the most sensitive to the device capital investment cost, amongst all devices in 2050. The sensitivity of annual costs of hybrid heat pumps to the device investment cost decreases with decreasing household insulation quality, as greater fractions of the annual space heating demand are satisfied by the hydrogen boiler component.
4) Annual costs per household in 2050 using hybrid heat pumps are mostly lower than those of hydrogen boilers. Under high levels of household insulation, and high energy tariffs, electric ground source heat pumps can be cheaper than hybrid heat pumps, however, hybrid heat pumps and hydrogen boilers are mostly cheaper than air and ground source heat pumps, annually, for terraced houses in 2050.
5) Theoretical calculations of annual heat demand per household are often lower than actual consumption levels by up to 25% for houses with insulation label A and B, but are often higher than actual consumption levels by 6% for houses of insulation label C, to 50% for houses with insulation label G.

6. Cost of Each Decarbonisation Pathway

The present study assumes that the electricity and heat infrastructure of 2050 will be based on 100% renewable energy coming from a combination of renewable energy generation technologies. Decarbonisation of the residential heating sector can be achieved in several ways. The present study investigates three possible technologies to decarbonise the residential heating sector of the Netherlands for the year 2050 – using electric heat pumps, hybrid heat pumps or hydrogen boilers. The aim is to determine which of the three decarbonisation strategies is the most cost effective. The cost of each pathway depends on the annual cost per household for each decarbonisation technology, for each type of residential dwelling in the Netherlands – Terraced houses, low and high-rise flats, semi-detached, and detached houses.

6.1 Assumptions for Dwellings in 2050

According to CBS Statline, 41% of Dutch households live in terraced housing, 32% in flats, 15% in detached and 12% in semi-detached homes. [58] In order to find the total cost per decarbonisation pathway for the present study, a number of assumptions have been made regarding the future housing stock of the Netherlands by the year 2050. The assumptions have been summarised in Table 6.1. In the table, the second column gives the housing composition of the Netherlands in the year 2020. The source of the numbers is the study "A Climate Neutral Heat for the Built Environment - Update 2016" by CE Delft. [33]

In their 2020 report "Hydrogen as an Option for Climate-Neutral Heat in Existing Buildings", TNO projected the number of houses in the Netherlands to be 9 million by the year 2050, which will be used in the present study. [60] A further assumption is that all dwellings will be occupied in the year 2050. The percentage distribution of houses as outlined by CBS Statline is assumed to be the same across the seven insulation labels in the present study. Finally, it is assumed that 50% of the flats are high-rise flats. The total number of houses for this study is thus similarly assumed to be 9 million. The total annual cost of each pathway is the sum of all the annual costs per household for all types of residential dwellings.

Table 6.1 – Assumptions Regarding Dwellings in 2050

Insulation Label	Number of dwellings in 2020 (millions)	Number of dwellings in 2050 (millions)	Terraced Houses	Low-rise Flats	High-rise Flats	Semi-detached houses	Detached Houses
A	0.30	0.35	0.14	0.05	0.06	0.04	0.05
B	2	2.30	0.95	0.37	0.37	0.28	0.35
C	1.30	1.50	0.62	0.24	0.24	0.18	0.22
D	2	2.30	0.95	0.37	0.37	0.28	0.35
E	1.40	1.60	0.67	0.26	0.26	0.2	0.25
F	0.60	0.70	0.28	0.11	0.11	0.08	0.11
G	0.10	0.11	0.04	0.02	0.02	0.02	0.02

6.2 Device Assumptions

For electric air and ground source heat pumps, the investment costs are taken in the upper range of the device investment cost figures given by various source, outlined in 'Model Inputs and Methodology'. For both air and ground source heat pumps, the device capital investment cost is assumed to fall by 17% with respect to present day prices, by 2050, based on the lower range of cost reduction estimates by 2050 from various sources [40] (collectively known as high device capital investment cost assumptions). For hybrid heat pumps, the device capital investment cost is assumed to fall by 30% with respect to current prices, by 2050, a figure given by many sources. In the 'Discussion' chapter, total annual cost per pathway will be calculated for lower device capital investment costs for electric heat pumps, and will be compared with the results of this section. Cost reduction factor of 0.8 is applied to investment cost of low temperature radiators, and a factor of 0.75 is applied to household renovation costs by 2050, based on [10]. The assumptions have been summarized in Table 6.2. ASHP refers to air source heat pumps, GSHP to ground source heat pumps, HHP refers to hybrid heat pumps and HB refers to hydrogen boilers. For the all-electric heat pump pathway, the combination of air and ground source heat pumps that has the lowest annual cost was first found, and then used to calculate the overall cost of the all-electric heat pump pathway.

Table 6.2 - Investment costs and device lifetimes for boilers, heat pumps and hybrid heat pumps in 2050

Decarbonisation Device	HB	ASHP	GSHP	HHP
Cost Per Unit Area (euros/$\boldsymbol{m^2}$)	9	66	77	24
Renovation Cost Reduction Factor	-	0.75	0.75	-
Radiator Cost Reduction factor	-	0.8	0.8	-
Device Lifetime (years)	15	15	15	15

6.3 Total Annual Cost of Each Decarbonisation Pathway in 2050

Table 6.3 compares the total annual cost per pathway of the decarbonisation technologies considered for the present study, in 2050. In the table, HHP refers to hybrid heat pumps, HB to hydrogen boilers, and 'Electric' refers to the all-electric heat pump option, Pel refers to electricity tariffs, PHyd to hydrogen tariffs.

Table 6.3 – Comparison of Annual Cost per Pathway of Each Decarbonisation Technology in 2050

Pel (€/kWh)	PHyd (€/kWh)	Electric	HHP	HB
0.081	0.046	Billion EUR 15.82	Billion EUR 10.07	Billion EUR 9.03
0.092	0.050	Billion EUR 16.24	Billion EUR 10.63	Billion EUR 9.62
0.106	0.060	Billion EUR 16.58	Billion EUR 11.86	Billion EUR 11.14
0.110	0.074	Billion EUR 16.71	Billion EUR 13.52	Billion EUR 13.17
0.134	0.078	Billion EUR 17.42	Billion EUR 14.23	Billion EUR 13.77

The electricity tariffs represent the levelized system cost of the 100% renewable electricity generation system of 2050 (including levelized cost of electricity generation, curtailment, transmission and storage) range of 0.057 – 0.110 euros/kWh, plus the electricity retail mark up of 0.024 euros/kWh. The hydrogen tariffs represent the levelized hydrogen production cost estimate range in 2050, 0.028 – 0.067 euros/kWh, plus hydrogen pipeline transmission cost of 0.0051 euros/kWh, plus the hydrogen retail mark up of 0.012 euros/kWh. The selection of energy tariffs has been detailed in 'Model Inputs and Methodology' (Sections 3.2 – 3.6).

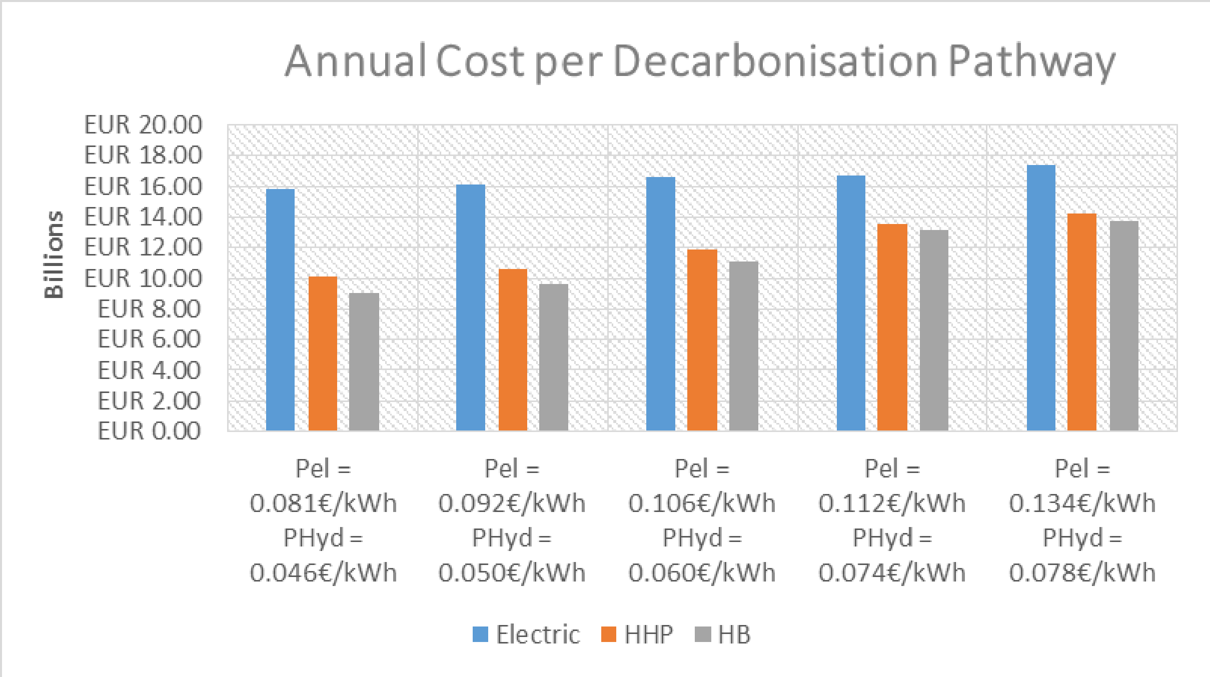


Fig. 6.1 – Comparison of Annual Cost per Decarbonisation Pathway at Different Energy Tariffs in 2050

Under the assumptions in 6.2, the electric heat pump pathway has the highest annual cost for all energy (electricity) tariffs in 2050. Hydrogen boilers have the lowest annual cost. The hydrogen boiler pathway has annual costs between 9.03 billion euros and 13.77 billion euros. The electric heat pump option (lowest cost combination of air and ground source heat pumps for each electricity tariff) has annual costs between 15.82 billion euros and 17.42 billion euros. The annual costs of the hybrid scenario range from 10.07 billion euros, to 14.23 billion euros. However, we have seen in Chapter 5 that the total annual costs per household are heavily dependent on device capital investment costs for electric air and ground source heat pumps in 2050. The annual cost per pathway will be calculated for modified device capital investment costs of electric heat pumps in the 'Discussion' chapter, and compared with the results in Table 6.3. Also, the effect of reducing household insulation costs on the annual costs of hybrid heat pumps and hydrogen boilers will be studied in the 'Discussion' chapter.

Table 6.4 shows the sensitivity of the total annual cost of each decarbonisation pathway to the electricity and hydrogen tariffs. For the hybrid scenario, it is assumed that for each electricity tariff that applies to the electric heat pump component, the corresponding hydrogen tariff applies to the hydrogen boiler component, in Table 5.5, same as in the calculation for annual cost per household. (For example, when the electricity tariff is 0.106 euros/kWh for the electric heat pump component of the hybrid heat pump, the hydrogen tariff for the hydrogen boiler component is 0.060 euros/kWh). In Table 6.4, Average Sensitivity refers to the sensitivity over the whole range of electricity and hydrogen tariffs in 2050, as the lowest and highest values of the range has been used to calculate the change in cost over the entire range, for ΔP.

Table 6.4 – Sensitivity of Total Annual Cost per Decarbonisation Pathway to Electricity and Hydrogen Tariffs in 2050

Decarbonisation Device	% Increase in Electricity and Hydrogen Tariffs (ΔP)	% Increase in Annual Cost per Decarbonisation Pathway in 2050 (ΔC)	Average Sensitivity ($\frac{\Delta C}{\Delta P}$)
Electric Heat Pumps	67	10.11	0.15
Hybrid Heat Pumps	67	41.31	0.62
Hydrogen Boilers	67	52.49	0.78

From Table 6.4, it can be seen that the uncertainties in electricity and hydrogen tariffs lead to large uncertainties in the annual cost per decarbonisation pathway – the greatest uncertainty lies in the annual cost of the hydrogen boiler scenario, with total annual costs of electric heat pumps having much lower sensitivities to the electricity tariffs than those of both hybrid heat pumps and hydrogen boilers. However, using the results of Table 6.3, the annual cost for the hydrogen boiler pathway when hydrogen tariffs are 0.078 euros/kWh (highest hydrogen tariff from tariff input range), are lower than the annual costs of electric heat pumps when electricity tariffs are 0.081 euros/kWh (lowest electricity tariff from tariff input range), for 2050. The sensitivity of hybrid heat pumps to changes in electricity tariff alone (and changes in hydrogen tariff alone) will be studied in the next chapter.

Other uncertainties also exist with device capital investment costs, household renovation cost reductions and cost reductions of low temperature radiators, as detailed earlier in this report, the effect of these uncertainties on the total annual cost for each pathway are also studied in the next chapter. The effect of household renovations on the overall annual cost per pathway in the hybrid heat pump and hydrogen boiler scenarios are also studied in the next chapter.

7. Discussion

In the previous chapter, the annual cost per decarbonisation pathway in 2050 was found and the three pathways were compared graphically. It was found that the hydrogen boiler pathway was the cheapest annually for all energy tariffs in 2050 (hydrogen tariffs), with annual costs between 9.03 billion euros and 13.77 billion euros. The electric heat pump option (lowest cost combination of air and ground source heat pumps for each electricity tariff) was the most expensive for all electricity tariffs, with annual costs between 15.82 billion euros and 17.42 billion euros. The annual costs of the hybrid scenario range from 10.07 billion euros, to 14.23 billion euros.

However, there is a wide variation in device capital investment cost figures for air and ground source heat pumps – estimates range from 5000 – 6500 euros/device for air source heat pumps at the lower end of the range of estimates, and from 10000 – 14500 euros at the higher end of the range, based on [40]. Ground source heat pump investment cost estimates also range from 8500 - 12000 euros/device to 12000 – 16500 euros/device, based on [41]. As seen in Chapter 5, device capital investment costs have the most influence on total annual cost per household for air and ground source heat pumps, compared to renovation cost reductions, electricity tariffs, and low temperature radiator cost reductions in 2050.

In addition to device capital investment cost estimates varying widely, there is also a wide variation in the estimates of device capital cost reductions by 2050, with respect to current device capital costs, from [40] and [41]. For air source heat pumps, reductions in the device capital cost by 2050, from current costs, range from 17% - 33%. For ground source heat pumps, the estimates range from 17% - 27%, with respect to current costs, by 2050. In Chapter 6, the annual cost per pathway was calculated by first assuming air source heat pumps cost between 10000 to 14500 euros/device, including VAT, and ground source heat pumps cost between 12000 and 16500 euros/device, including VAT. The device capital investment cost was then annuitized over the lifetime of each device (15 years for both device) after subtracting VAT, to calculate annual costs per household for each dwelling type.

In this chapter, the annual cost for the electric heat pump pathway in 2050 is calculated by first assuming air source heat pumps cost between 5000 to 6500 euros/device, including VAT, and ground source heat pumps cost between 8500 and 12000 euros/device, including VAT. Air source heat pumps are assumed to be 33% cheaper by 2050 compared to current prices, and ground source heat pumps are assumed to be 27% cheaper. The device capital investment cost are then annuitized over the lifetime of each device (15 years for both device) after subtracting VAT (21%), to calculate annual costs per household for each dwelling type (collectively known as low device capital investment cost assumptions). Finally, the cheapest combination of air and ground source heat pumps for each type of dwelling in 2050 is selected as the final annual cost of the electric pathway. Cost reduction factor of 0.8 with respect to current costs, is applied to investment cost of low temperature radiators, and a factor of 0.75 is applied to household renovation costs by 2050, based on [10]. The device assumptions are summarized in Table 7.1.

Table 7.1 - Investment costs and device lifetimes for boilers, heat pumps and hybrid heat pumps in 2050

Type of home	HB	ASHP	GSHP	HHP
Cost Per Unit Area (euros/$\boldsymbol{m^2}$)	9	25 (62% reduction compared to Table 6.2)	49 (36% reduction compared to Table 6.2)	24
Device Lifetime (years)	15	15	15	15

In Chapter 6, it was assumed that households with hybrid heat pumps and hydrogen boilers would not undergo renovation to improve household insulation in 2050. However, annual costs per household are directly dependent on annual heat demand, of which space heating demand makes up 63% – 72% (households of insulation label A), to over 95% in households of insulation label G in 2050. Space heating demand is directly related to household insulation quality and improving household insulation levels could reduce costs in the hybrid and hydrogen scenarios in 2050 as well. Cost reductions in the hybrid and hydrogen pathways are also investigated in this chapter. In all tables in this chapter, HHP refers to hybrid heat pumps, ASHP to air source heat pumps, GSHP to ground source heat pumps, and HB to hydrogen boilers.

7.1 Annual Costs under Low Device Capital Investment Cost Assumptions

Table 7.2 compares the annual cost per decarbonisation pathway of electric air and ground source heat pumps, hybrid head pumps, and hydrogen boilers in the Netherlands in 2050. In the table, HHP refers to hybrid heat pumps, HB to hydrogen boilers, and ‘Electric’ refers to the all-electric heat pump option, Pel refers to electricity tariffs, PHyd to hydrogen tariffs. The electricity tariffs represent the levelized system cost of the 100% renewable electricity generation system of 2050 (including levelized cost of electricity generation, curtailment, transmission and storage) range of 0.057 – 0.110 euros/kWh, plus the electricity retail mark up of 0.024 euros/kWh. The hydrogen tariffs represent the levelized hydrogen production cost estimate range in 2050, 0.028 – 0.067 euros/kWh, plus hydrogen pipeline transmission cost of 0.0051 euros/kWh, plus the hydrogen retail mark up of 0.012 euros/kWh.

Under electricity tariffs of 0.081 – 0.106, all electric heat pumps (cheapest combination of air source and ground source heat pumps for each type of dwelling in 2050, for each electricity tariff) have the highest annual costs per household, at 11.85 – 12.95 billion euros annually in 2050. Hydrogen boilers have the lowest annual costs for all hydrogen tariff assumptions in 2050. Under electricity tariffs of 0.110 – 0.134 euros/kWh (and hydrogen tariffs of 0.074 – 0.110 euros/kWh), hybrid heat pumps have the highest annual cost per household, with 13.51 – 14.23 billion euros annually.

Table 7.2 – Comparison of Annual Cost per Pathway of Each Decarbonisation Technology in 2050

Pel (€/kWh)	PHyd (€/kWh)	Electric	HHP	HB
0.081	0.046	Billion EUR 11.85	Billion EUR 10.07	Billion EUR 9.03
0.092	0.050	Billion EUR 12.34	Billion EUR 10.63	Billion EUR 9.62
0.106	0.060	Billion EUR 12.95	Billion EUR 11.86	Billion EUR 11.11
0.110	0.074	Billion EUR 13.13	Billion EUR 13.51	Billion EUR 13.18
0.134	0.078	Billion EUR 14.19	Billion EUR 14.23	Billion EUR 13.77

Table 7.3 shows the sensitivity of the annual cost per household of electric air and ground source heat pumps to the device capital investment cost reduction. From the table, it is seen that for a 62% decrease in device capital investment cost of air source heat pumps with respect to the device capital investment cost assumptions in Chapter 6 ‘Total Cost of Each Decarbonisation Pathway’, and a 36% decrease in the capital investment cost of ground source heat pumps (compared to the cost assumptions in Chapter 6) led to a 18.54% - 25.05% decrease in annual cost of the electric heat pump pathway. The uncertainties in electricity and hydrogen tariffs lead to uncertainties in the most expensive pathway – hybrid heat pumps are cheaper than all-electric heat pumps under low-moderate energy tariffs (electricity tariff = 0.081 – 0.106 euros/kWh, hydrogen tariff = 0.046 – 0.074 euros/kWh), but all-electric heat pumps are cheaper than hybrid heat pumps for high energy tariffs. However, the hydrogen boiler decarbonisation pathway remains the cheapest option for all hydrogen tariffs.

Table 7.3 – Sensitivity of Annual Cost per Pathway of Electric Heat Pumps to Device Capital Investment Cost for 2050

Pel (€/kWH)	PHyd (€/kWH)	% Reduction in Device Capital Investment Cost (ΔP) Compared to Table 6.3		% Reduction in Annual Cost per Pathway (ΔC) Compared to Table 6.3
		ASHP	GSHP	
0.081	0.046	62	36	25.05
0.092	0.050	62	36	24.02
0.106	0.060	62	36	21.90
0.110	0.074	62	36	21.42
0.134	0.078	62	36	18.54

The annual costs per decarbonisation pathway of electric heat pumps, hybrid heat pumps and hydrogen boilers, considering reduced investment cost of air and ground source heat pumps with respect to Chapter 6, are also compared in Figure 7.1. In the figure, HHP refers to hybrid heat pumps, HB to hydrogen boilers, and ‘Electric’ refers to the all-electric heat pump option, Pel refers to electricity tariffs, PHyd to hydrogen tariffs

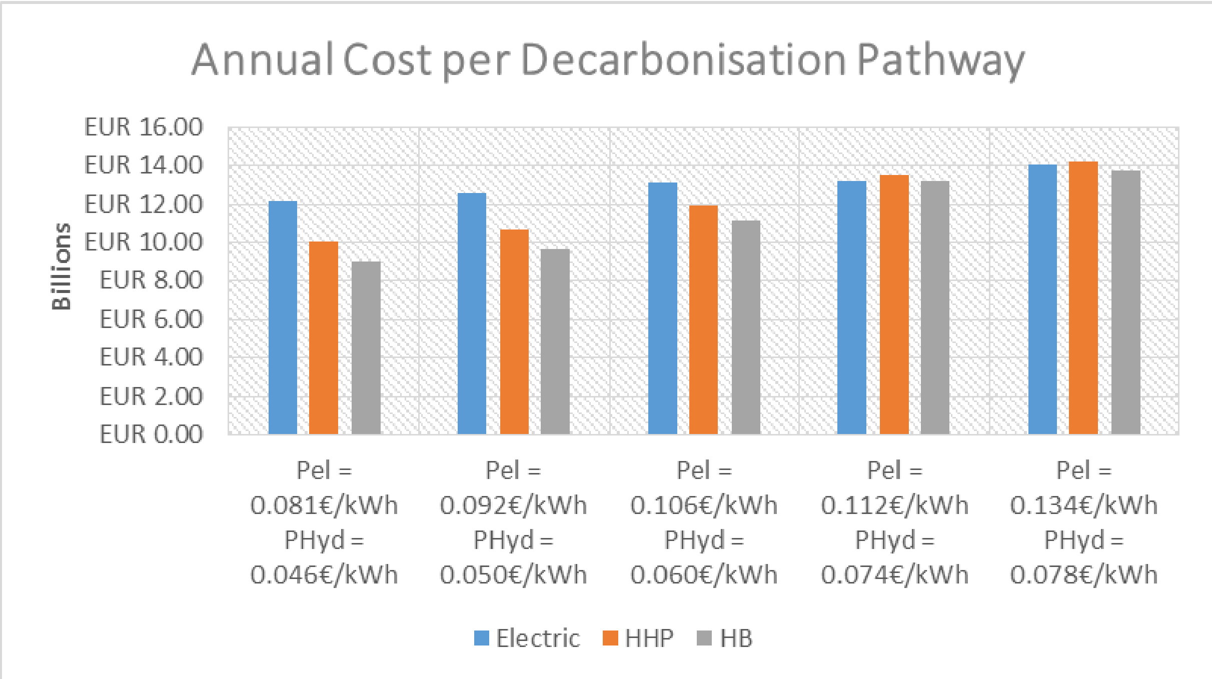


Fig. 7.1 – Comparison of Annual Cost per Decarbonisation Pathway at Different Energy Tariffs for Reduced Capital Investment Costs for Electric Air and Ground Source Heat Pumps by 2050

7.2 Performing Renovations When Using Hybrid Heat Pumps and Hydrogen Boilers

In the previous section, and in Chapter 6, the annual costs of the hybrid heat pump and hydrogen pathways were calculated by assuming that households of poor insulation quality do not undergo renovations to improve their insulation label in 2050, unlike the case for all-electric heat pumps. For all-electric heat pumps, all households of insulation label D and lower were assumed to undergo renovations to improve their insulation label to C, the minimum acceptable insulation quality for effective heat pump operation, according to recommendations by CE, given in [40][41]. CE does not give similar recommendations for hybrid heat pumps, and houses that run will run hydrogen boilers in 2050 are also assumed not to undergo renovations so far in the present study.

The improvement of household insulation levels will lead to a decrease in annual heat demand per household, and consequently, a decrease in annual energy cost per household. However, renovations to improve household insulation levels are expensive, in some cases, the energy savings do not compensate for the increase in annual costs due to household renovations. Based on these two facts, it was seen that households of insulation label E, F and G would see a decrease in total annual cost per household by improving their insulation levels to label D, each (label E renovated to label D, label F renovated to label D, label G renovated to label D), for both, hybrid heat pumps, and hydrogen boilers, for all energy tariffs. Insulation cost reduction factor of 0.75 by 2050 compared to present values was applied for all pathways, for all energy tariffs. Device capital investment costs are from Table 7.1 (low device capital investment cost assumptions).

Table 7.4 – Comparison of Annual Cost per Pathway of Each Decarbonisation Technology in 2050

Pel (€/kWh)	PHyd (€/kWh)	Electric	HHP	HB
0.081	0.046	Billion EUR 11.85	Billion EUR 9.73	Billion EUR 8.62
0.092	0.050	Billion EUR 12.34	Billion EUR 10.18	Billion EUR 9.10
0.106	0.060	Billion EUR 12.95	Billion EUR 11.18	Billion EUR 10.29
0.110	0.074	Billion EUR 13.13	Billion EUR 12.44	Billion EUR 11.96
0.134	0.078	Billion EUR 14.19	Billion EUR 13.01	Billion EUR 12.44

Table 7.5 – Sensitivity of Annual Cost per Pathway of Hybrid Heat Pumps and Hydrogen Boilers to Household Renovations

Pel (€/kWH)	PHyd (€/kWH)	Cost reduction Factors (ΔP) by 2050		% Reduction in Annual Cost per Pathway (ΔC) Compared to Table 7.3	
		Renovation	Low Temperature Radiators	HHP	HB
0.081	0.046	0.75	0.8	3.31	4.52
0.092	0.050	0.75	0.8	4.23	5.21
0.106	0.060	0.75	0.8	5.74	7.41
0.110	0.074	0.75	0.8	7.93	9.24
0.134	0.078	0.75	0.8	8.57	9.66

Table 7.4 gives the annual cost per pathway of electric heat pumps, hybrid heat pumps and hydrogen boilers in 2050 taking into account the annual cost of household renovations to improve the insulation quality of houses of insulation label E, F and G, to insulation label D, and taking into account cost reduction factors of low temperature radiators and household renovation costs. In the table, HHP refers to hybrid heat pumps, HB to hydrogen boilers, and 'Electric' refers to the all-electric heat pump option, Pel refers to electricity tariffs, PHyd to hydrogen tariffs. Performing renovating in households that run hybrid heat pumps and hydrogen boilers leads to a reduction in annual costs for both pathways.

From Table 7.5, we see that the reductions in annual costs are 3.31 – 8.57% for air source heat pumps, and 4.52 – 9.66% for ground source heat pumps. Due to the renovations, the all-electric heat pump option becomes the most expensive option for all energy tariffs. Hydrogen boilers remain the cheapest option annually in 2050, for all hydrogen tariffs. The annual costs per decarbonisation pathway in 2050 are also compared in Fig 7.2. In the figure, HHP refers to hybrid heat pumps, HB to hydrogen boilers, and 'Electric' refers to the all-electric heat pump option, Pel refers to electricity tariffs, PHyd to hydrogen tariffs

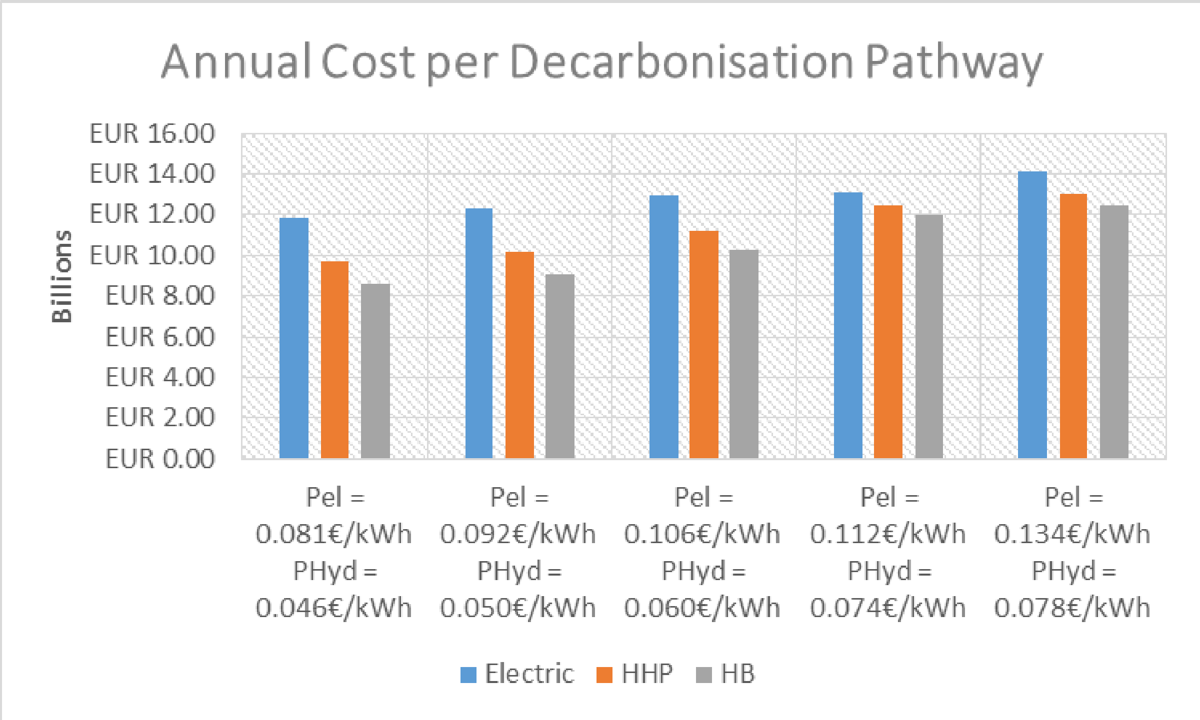


Fig. 7.2 – Comparison of Annual Cost per Decarbonisation Pathway at Different Energy Tariffs When Households of Insulation Label E, F, and G are Renovated to Insulation Label D When Using Hybrid Heat Pumps and Hydrogen Boilers in 2050

7.3 Electricity Tariff Increase from Grid Strengthening due to Increased Renewables

In the present study, the electricity tariff inputs for 2050 are assumed taking into account the levelized system cost of electricity production – comprised of the levelized cost of electricity generation, transmission, storage and curtailment, and the electricity retail mark up. The annual costs per household in the all-electric heat pump pathway include the cost of strengthening household connection to the distribution grid in the case of mass deployment of heat pumps in 2050, from a 1 X 35A connection, to a 3 X 25A connection, as a flat rate per household.

The energy generation system (electricity and heat) of 2050 is assumed in the present study to be 100% renewable energy based, including energy (electricity and heat) storage, and flexibility technologies to ensure security of energy supply, collectively known as reinforcements to the transmission grid. Increased heat pump deployment will lead to an increase in electricity peak load demand, especially during the heating season. Studies done for the UK, as detailed in [61] and [62], have shown that increased deployment of heat pumps could lead to an increase in peak electricity demand, which would require investment in additional renewable energy generation capacity, increased energy storage to cover mismatches, and investment in additional flexibility technologies to provide security of energy supply.

The additional investment costs would increase overall system costs, and likely will lead to additional costs that have so far not been assumed in the electricity tariffs for 2050 in the present study. The increase in electricity tariffs would depend on the increase in renewable energy generation capacity required, and the technologies used to increase flexibility and strengthen and expand the grid. Other studies ([61], [62]) in the past have studied this effect of increased heat pump deployment, and studied the resulting increase in peak load. These studies have not, however, correlated the increase in peak electricity requirement with the possible resulting increase in electricity tariffs. Also, in the previous chapter of this report, the sensitivity of the total annual cost of the hybrid pathway in 2050 was calculated by assuming increases in electricity and hydrogen tariff inputs simultaneously.

The effect of electricity tariffs alone (or hydrogen tariffs alone) on the total annual cost of the hybrid pathway has not been studied as yet. According to carbonbrief.org, strengthening the transmission grid to integrate renewable energy sources are estimated to add £5 - £20 (0.55 – 2.2 euro cents/kWh in 2020 euros) to the cost of transitioning the current energy system of the UK to fully renewable energy. [63]

In order to include the costs of strengthening the electricity transmission grid in the event of increased deployment of electric and hybrid heat pumps, study the sensitivity of electricity tariffs alone on total annual costs of the hybrid pathway, and due to the lack of exact figures for the cost of transmission grid strengthening for 2050, the electricity tariffs in this section are assumed to increase by an average of 2 cents per kWh, based on [63], to be added to the electricity tariff inputs from Table 5.5. Device investment costs are from Table 7.1 (low device capital investment cost assumptions). The electricity and hydrogen tariff inputs for 2050 are given in Table 7.6. Households of insulation label E, F and G are assumed to be renovated to insulation label D in 2050 in the hybrid and hydrogen scenarios. Cost reduction factors of 0.75 for household renovation costs, and 0.8 for low temperature radiator costs by 2050, with respect to present-day costs, are assumed in all pathways.

Table 7.6 –Electricity and Hydrogen Tariff Inputs for 2050

Electricity Tariff Increase from Grid Strengthening (euros/kWh)	Electricity Tariff (euros/kWh)	Hydrogen Tariffs (euros/kWh)
0.02	0.101	0.046
0.02	0.112	0.050
0.02	0.126	0.060
0.02	0.130	0.074
0.02	0.154	0.078

Table 7.7 – Comparison of Annual Cost per Pathway of Each Decarbonisation Technology

Pel (€/kWh)	PHyd (€/kWh)	Electric	HHP	HB
0.101	0.046	Billion EUR 12.73	Billion EUR 9.91	Billion EUR 8.62
0.112	0.050	Billion EUR 13.17	Billion EUR 10.36	Billion EUR 9.10
0.126	0.060	Billion EUR 13.77	Billion EUR 11.36	Billion EUR 10.29
0.130	0.074	Billion EUR 13.94	Billion EUR 12.62	Billion EUR 11.96
0.154	0.078	Billion EUR 14.97	Billion EUR 13.20	Billion EUR 12.44

As expected, the increase of electricity tariffs in 2050 by 2 cents/kWh leads to a rise in annual cost of the electric and hybrid heat pump pathways. The overall results do not change – electric heat pumps remain the most expensive option for all electricity tariffs, hydrogen boilers are the cheapest annually for all hydrogen tariffs, and hybrid heat pumps are cheaper than electric heat pumps for all energy tariffs. In addition, increasing the electricity tariff by 2 cents/kWh (increase of 13 – 20%) increases the annual cost of the hybrid pathway by 1.46 – 1.85%. The annual costs per decarbonisation pathway in

2050 are also compared in Fig 7.3. In the figure, HHP refers to hybrid heat pumps, HB to hydrogen boilers, and 'Electric' refers to the all-electric heat pump option, Pel refers to electricity tariffs, PHyd to hydrogen tariffs

Table 7.8 – Sensitivity of Annual Cost per Pathway of Electric and Hybrid Heat Pumps to Electricity Tariffs

Pel (€/kWH)	**PHyd (€/kWH)**	**% increase in Electricity Tariffs**	**% Increase in Annual Cost per Pathway (ΔC) Compared to Table 7.5**		**Sensitivity ($\frac{\Delta C}{\Delta P}$)**	
			Electric	HHP	Electric	HHP
0.101	0.046	20	7.43	1.85	0.37	0.092
0.112	0.050	18	6.73	1.78	0.37	0.099
0.126	0.060	16	6.33	1.61	0.40	0.101
0.130	0.074	15	6.17	1.45	0.41	0.097
0.154	0.078	13	5.50	1.46	0.42	0.110

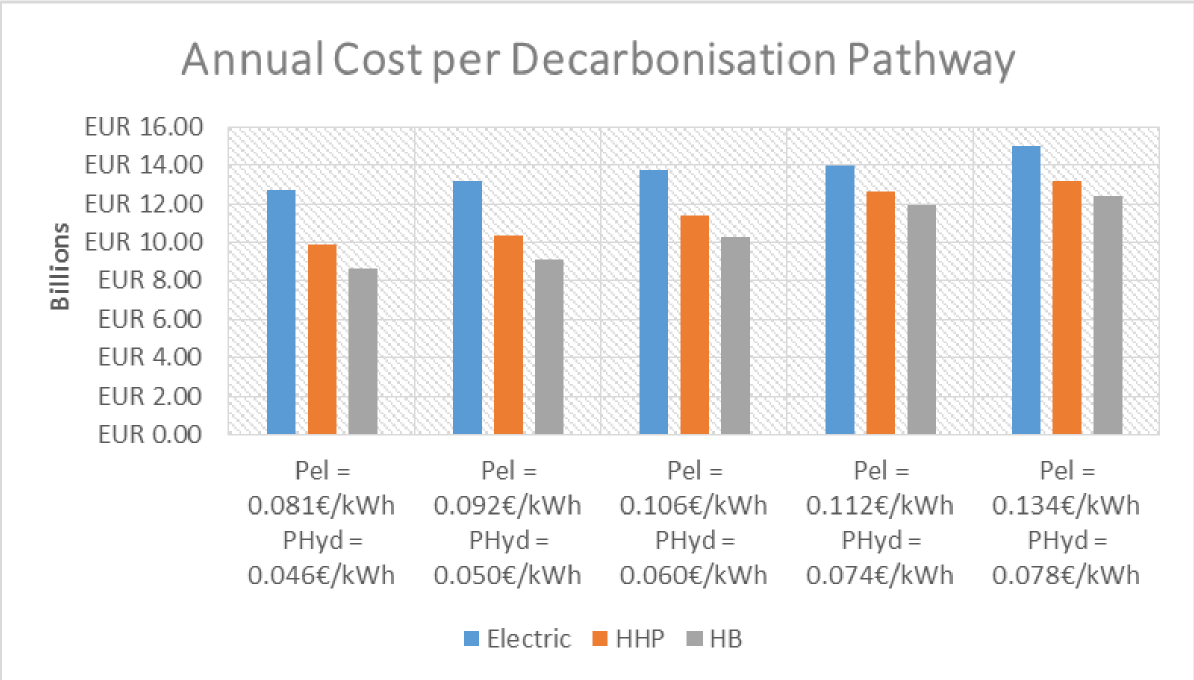


Fig. 7.3 – Comparison of Annual Cost per Decarbonisation Pathway at Different Energy Tariffs When Electricity Tariffs are Assumed to Increase by 2 cents/kWh due to Grid Strengthening in 2050

7.4 Sensitivity of Hybrid Heat Pump Annual Costs to Hydrogen Tariffs

In the previous section, the sensitivity of the total annual cost of the hybrid heat pump pathway in 2050 to the electricity tariff alone was investigated. It was found that the annual cost of the hybrid heat pump pathway had a sensitivity of 0.092 – 0.11 to the electricity tariffs, with three of the five sensitivity values being 0.099, 0.097 and 0.101. Similar to the electricity tariffs, green hydrogen production costs estimates for 2050 vary widely, giving rise to uncertainty in determining best decarbonisation option.

In this section, the sensitivity of the total annual cost of the hybrid heat pump pathway to the hydrogen tariffs alone is investigated.

The hydrogen tariffs for 2050 selected in the present study are based on- figures for green hydrogen production costs for Europe and worldwide, obtained from literature ([24], [26]), and by assuming dedicated offshore wind energy capacity in the North Sea, with levelized cost of energy from the turbines assumed to range from 20 – 40 euros/MWh in 2050, also based on literature. The hydrogen tariffs for 2050 selected for this study range from 0.046 euros/kWh to 0.078 euros/kWh, including the cost of pipeline transmission from the North Sea production facilities.

In this section, the annual cost of the hybrid scenario is calculated for an electricity tariff of 0.106 euros/kWh and a hydrogen tariff of 0.074 kWh, and compared with the annual cost when electricity tariff is 0.106 euros/kWh and hydrogen tariff is 0.060 euros/kWh in Table 7.9. Households of insulation label E, F and G are assumed to be renovated to insulation label D in 2050 in the hybrid and hydrogen scenarios. Device capital investment costs are from Table 7.1 (low device capital investment cost assumptions). Cost reduction factors of 0.75 for household renovation costs, and 0.8 for low temperature radiator costs by 2050, with respect to present-day costs, are assumed in all pathways.

Table 7.9 – Increase of Annual Cost of the Hybrid Pathway with Hydrogen Tariff Increase

Pel (€/kWh)	PHyd (€/kWh)	Annual Cost of Hybrid Pathway
0.106	0.060	Billion EUR 11.18
0.106	0.074	Billion EUR 12.40

From Table 7.9, we can see that when hydrogen tariffs increase from 0.060 euros/kWh to 0.074 euros/kWh (increase of 23.3%), the annual cost of the hybrid pathway rises by 10.91%, giving a sensitivity of 0.47 to the hydrogen tariffs. This value is higher than any of the sensitivity values (sensitivity to electricity tariff in 2050 ranges from 0.092 to 0.11) of annual cost of hybrid heat pumps with electricity tariffs in 2050. Uncertainties in hydrogen tariff will have a larger impact on the annual cost per pathway in the hybrid scenario, compared to electricity tariffs.

7.5 Lower Rate of Interest per Period

So far in this report, the capital investment costs (device capital investment cost, renovation cost, cost of low temperature radiators, cost of disconnecting from the gas grid, and cost of strengthening household distribution grid connection) have been annuitized over the lifetime of the device (or the lifetime of household insulation, for renovation investments) using a discount rate of 7% per year. This discount rate was used based on 'Barriers to investment in utility-scale variable renewable electricity (VRE) generation projects' by Jing Hu et al. who estimated discount rates between 6% and 14% for renewable energy project investments in European countries. [64]

In "Common misunderstandings in life cycle costing analyses and how to avoid them" by van den Boomen et al, the recommended social discount rate for public projects in the Netherlands is set between 3% - 5%, with the discount rate for public infrastructure projects recommended at 4.5%. [65] In "Discount rates in energy system analysis Discussion Paper" in 2015, it was stated that energy system models used in Europe to make policy decisions, such as PRIMES, use discount rates of 9% for energy generation projects in Europe, and use a discount rate of 3.1 – 3.7% for household space heating, for the evaluation of energy efficiency policies in the EU. The paper also mentions the discount rate used by Germany for Renewable Energy projects is 7%. [66]

Discount rates have a large impact on the annual costs per decarbonisation pathway in 2050. Lower discount rates mean lower annual cost per household, and per decarbonisation pathway. Uncertainties in the discount rate to be used leads to uncertainties in determining which decarbonisation pathway of 2050 in the Netherlands would have the least annual costs per household, comprised of the cumulative annual cost per household – only household costs are calculated, not social costs. In this section, the effect of discount rate on the annual costs per decarbonisation pathway have been investigated, and present in Table 7.11.

Electricity tariffs are assumed to include the cost of reinforcing the electricity transmission grid (adding 2 cents/kWh to the electricity tariffs from Table 5.5, hydrogen tariffs are taken from Table 5.5 with no change). A discount rate of 4% per annum has been taken, based on [64] and [65]. Both discount rates are net of inflation rate per annum as the inflation rate is variable and adds greater uncertainty to the calculations. The electricity and hydrogen tariff assumptions used in the present section are given in Table 7.11. Households of insulation label E, F and G are assumed to be renovated to insulation label D in 2050 in the hybrid and hydrogen scenarios. Device capital investment costs are from Table 7.1 (low device capital investment cost assumptions). Cost reduction factors of 0.75 for household renovation costs, and 0.8 for low temperature radiator costs by 2050, with respect to present-day costs, are assumed in all pathways.

Table 7.10 –Electricity and Hydrogen Tariff Inputs for 2050

Electricity Tariff Increase from Grid Strengthening (euros/kWh)	Electricity Tariff (euros/kWh)	Hydrogen Tariffs (euros/kWh)
0.02	0.101	0.046
0.02	0.112	0.050
0.02	0.126	0.060
0.02	0.130	0.074
0.02	0.154	0.078

Table 7.11 – Comparison of Annual Cost per Pathway of Each Decarbonisation Technology

Pel (€/kWh)	PHyd (€/kWh)	Electric	HHP	HB
0.101	0.046	Billion EUR 11.52	Billion EUR 9.08	Billion EUR 8.10
0.112	0.050	Billion EUR 11.94	Billion EUR 9.53	Billion EUR 8.58
0.126	0.060	Billion EUR 12.44	Billion EUR 10.53	Billion EUR 9.77
0.130	0.074	Billion EUR 12.58	Billion EUR 11.79	Billion EUR 11.44
0.154	0.078	Billion EUR 13.42	Billion EUR 12.36	Billion EUR 11.92

When compared with the annual cost per decarbonisation pathway in Table 7.7, reducing the discount rate from 7% to 4% per annum (decrease of 43%) reduces the annual cost per pathway in 2050 by 4.2 – 6% for the hydrogen boiler pathway, 6.4 - 8.4% for hybrid heat pumps, and 9.5 - 10.6% for all-electric heat pumps. The overall results do not change from the previous sections, electric heat pumps have the highest annual costs, while hydrogen boilers have the lowest cost, for all electricity and hydrogen tariffs in 2050. Hybrid heat pumps are cheaper than electric air and ground source heat pumps annually, for all energy tariffs (electricity and hydrogen).

In sections 7.3 and 7.4, the sensitivity of the annual costs of the hybrid pathway to the electricity tariffs (section 7.3) and hydrogen tariffs (section 7.4) alone, was found, for 2050. The sensitivity of the annual costs of the electric heat pump scenario to the electricity tariffs in 2050 ranged from 0.37 (electricity tariff increase of 0.081 – 0.101 euros/kWh) to 0.42 (electricity tariff increase of 0.134 – 0.154 euros/kWh). The sensitivity of the hybrid scenario for the same electricity tariff increase ranged from 0.092 – 0.11. The sensitivity of the annual cost of the hybrid scenario in 2050 to the hydrogen tariffs was found to be 0.47, while the sensitivity of the total annual costs of the hydrogen boiler pathway was found to be 0.68. It appears, from the results that annual costs of the hybrid scenario are less sensitive to electricity tariff changes than hydrogen tariff changes.

Table 7.8 – Sensitivity of Annual Cost per Pathway of Each Decarbonisation Pathway to Discount Rate

Pel (€/kWH)	**PHyd (€/kWH)**	**% Decrease in Discount Rate**	**% Decrease in Annual Cost per Pathway (ΔC) Compared to Table 7.7**			**Sensitivity ($\frac{\Delta C}{\Delta P}$)**		
			Electric	HHP	HB	Electric	HHP	HB
0.101	0.046	43	9.51	8.38	6.42	0.22	0.19	0.15
0.112	0.050	43	9.34	8.01	5.71	0.22	0.19	0.13
0.126	0.060	43	9.66	7.31	5.05	0.22	0.17	0.12
0.130	0.074	43	9.76	6.58	4.35	0.23	0.15	0.10
0.154	0.078	43	10.35	6.36	4.18	0.24	0.15	0.10

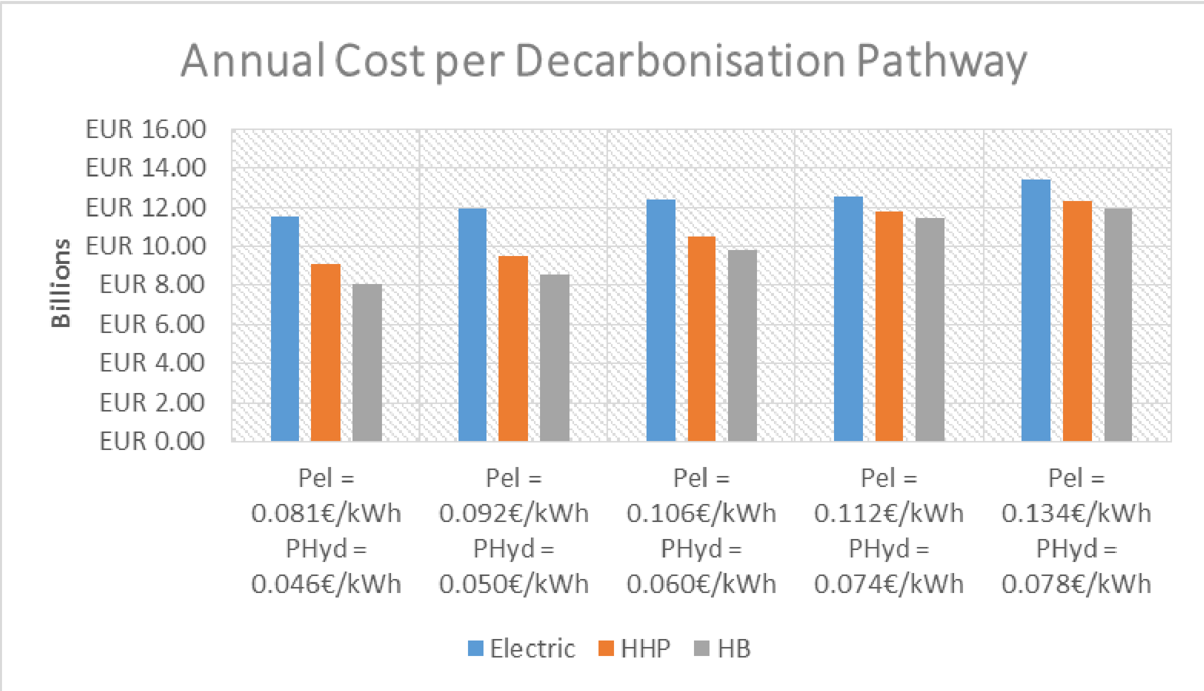


Fig. 7.4 – Comparison of Annual Cost per Decarbonisation Pathway at Different Energy Tariffs When Discount Rate is taken as 4% in 2050

From Table 7.11, the annual cost of the electric heat pump pathway is 11.52 billion euros in 2050 when the electricity tariffs are 0.101 euros/kWh. The hydrogen pathway costs 8.10 billion euros in 2050 when the hydrogen tariffs are 0.046 euros/kWh. The cost for the hybrid scenario is 9.08 billion euros. On increasing the hydrogen tariff from 0.046 euros/kWh to 0.060 euros/kWh (30% increase) and keeping electricity tariffs at 0.101 euros/kWh, and using the sensitivity value of 0.47 obtained from Table 7.9 for the hybrid scenario, the annual cost of the hybrid scenario increases from 9.08 billion euros in 2050, to 11.52 billion euros, which is equal to the annual cost of the air source heat pump scenario at electricity tariffs of 0.101 euros/kWh in 2050, for an increase of 57% in the hydrogen tariffs, from 0.046 euros/kWh, to 0.072 euros/kWh. When considering the range of hydrogen cost estimates for 2050 used in the present study, 0.072 euros/kWh is 7.7% lower than the highest hydrogen tariff estimate for 2050, 0.078 euros/kWh. We can say that the annual costs of the hybrid pathway are less than or equal to the annual costs of the electric heat pump pathway under present assumptions, for 93.3% of the estimated hydrogen tariff range for 2050.

For the hydrogen boiler scenario, from Table 7.11 and using the sensitivity of annual cost of hydrogen boilers to the hydrogen tariffs from Table 6.4, and applying the same method as the hybrid scenario, we see that the annual costs of the hydrogen boiler pathway are equal to the annual cost of the electric heat pump pathway when the electricity tariffs are 0.101 euros/kWh (lowest electricity tariff for 2050 in the present study) when hydrogen tariffs are 0.075 euros/kWh, which is 3.8% lower than 0.078 euros/kWh, the highest hydrogen tariff estimate for 2050 in the present study. The hydrogen scenario can be said to be cheaper than the electric heat pump scenario for 96.2% of the range of hydrogen tariff estimates used in the present study, for 2050. The certainties presented here represent relative certainties, under the circumstances of the assumptions used in the present study, for the Netherlands in 2050. The annual costs per decarbonisation pathway in 2050 with an annual discount rate of 4% are also compared in Fig 7.4. In the figure, HHP refers to hybrid heat pumps, HB to hydrogen boilers, and 'Electric' refers to the all-electric heat pump option, Pel refers to electricity tariffs, PHyd to hydrogen tariffs.

7.6 Comparison with Other Studies

Decarbonisation of the Dutch residential heating sector for 2050 can be achieved in more than one way. The present study has investigated three pathways – heating using electric heat pumps, hybrid heat pumps, and hydrogen boilers - to achieve decarbonisation of the residential heating sector of the Netherlands. Studies for other regions, such as the UK, have also compared the cost performance of these three decarbonisation pathways, albeit in different ways from the present study. The study "Analysis of Alternative UK Heat Decarbonisation Pathways" for the Committee on Climate Change, by Strbac, et al, Imperial College, compared the total cost of decarbonisation for three decarbonisation pathways – electric heating (heat pumps + resistive heating), hybrid electric and gas (or hydrogen) heating, and heating using hydrogen (or biomass) boilers. [5]

Another report titled "Cost Analysis of Future Heat Infrastructure Options", for the National Infrastructure Commission in the UK, was published in 2018, by Element Energy and E4Tech. The report detailed a study which was undertaken to analyse the costs of using, among others, electric and hybrid heat pumps, and hydrogen boilers at end-user sites, to limit the annual carbon dioxide emissions of the residential heat sector of the UK to below 10 Mt of carbon dioxide per year by 2050. The annual costs were analysed for the energy system of the UK as a whole, in the time frame 2015 – 2050. [62]

The study in [62] found hydrogen boilers to be the cheapest option, with electric heat pumps being the most expensive, in 2050. However, unlike the Imperial College study, Element Energy and E4Tech did not consider green hydrogen production, hydrogen was assumed to be produced by SMR (Steam Methane Reforming) in combination with Carbon Capture and Storage (CCS) only. In addition, the hybrid heat pumps are assumed to use natural gas (combined with CCS), not hydrogen, in the hybrid pathway. These assumptions limit the reduction of emissions in the hydrogen pathway to 20Mt – 22Mt of carbon dioxide per year from the residential sector, and 24Mt for the hybrid pathway. [62]

7.6.1 Comparison of Costs of Electric Heat Pumps with Other Studies

In the Imperial College Study, it was found that the annual system cost for the electric heating scenario was highly dependent on the capital investment cost for the entire energy system, which made up the majority of the overall costs in their whole energy system analysis. The study concluded that reducing the capital expenses of renewable energy generation technologies would lead to lower overall system costs for the electric decarbonisation pathway.

In the present study, it is assumed that the electricity generation system for 2050 in the Netherlands will be 100% renewable energy based, with electricity from the grid being used to supply energy to heat pumps at every household. The electricity tariffs used in the present study are based on the system Levelized Cost of Energy (LCoE) of this 100% renewable energy generation system, based on system levelized cost estimates from various sources. For renewable energy systems, there is no fuel utilised, in technologies such as solar photovoltaic power and wind energy generation, electricity is directly produced at the generation site and transmitted and distributed to end users (households). The LCoE is thus mainly a function of the capital costs of the renewable energy generation system – if the LCoE were to fall, the electricity tariffs would fall.

The study by Imperial College also noted the high dependence of annual costs of the costs of financing, decided by the discount rate in the study. A low discount rate led to increases in annual costs, a high discount led to reductions in annual cost compared to the central scenario. [5] The annual costs of the electric heat pump pathway in 2050 in the present study were also found to increase with the discount rate used, mainly leading to higher annual device capital investment costs (including the cost of low temperature radiators), and higher capital costs of household renovations.

The annual cost of the electric heat pump pathway in 2050 in the present study was found to be 1.90 billion euros higher when the energy tariffs were high, compared to the situation of low energy tariffs, including possible costs of strengthening the electricity transmission grid to accommodate increase renewable energy generation capacity, and imperial taking a discount rate of 4%, based on [65]. Based on the reasoning given earlier, and on the results by Imperial College, it can be concluded for the present study that lower capital costs of renewable energy generation would lead to lower system costs, lower electricity tariffs, and lower annual cost of the electric heat pump scenario in the Netherlands, in 2050.

In the study by Element Energy and E4Tech, it was found that the electric heat pump scenario was the most expensive, similar to the present study, when the electricity tariff is assumed to increase to account for the increase in peak electricity demand due to electrical heating. The discount rate used in the study was 3.5%. The increase in peak demand would require investment in greater capacity of renewable energy generation, potentially leading to an increase in electricity tariffs. The study also noted that electric heat pumps could only be used in buildings with adequate household thermal quality (insulation levels) and that a large number (10 million, of 26 million buildings) would require renovations to improve household insulation levels. [62]

It was found that the contribution to peak electricity load for heating would increase by 46GW for the UK in 2050 compared to 2018, leading to additional system costs which are up to 11% of the final annual cost. [62] For the present study, the assumed increase in electricity tariff by 2 cents/kWh, leads to an increase in annual cost of the electric heat pump pathway by 5.5% - 7% depending on the input electricity tariff for 2050, it appears that this is at least a comparable value with the Element Energy study for a first estimate, in the present study. In addition, sources such as [63] have also put the transmission grid reinforcement costs between 0.5 and 2 euro cents/kWh.

It was found in the Imperial College study that the overall system costs of the electric heat pump pathway was also highly dependent on the investment capital cost of the device – lower cost of heat pumps resulted in lower overall system costs. [5] In the present study, there is a difference of 3.6 – 3.7 billion euros between the annual costs of the electric heat pump pathway under low device capital investment cost assumptions, compared to the costs under high device capital investment cost assumptions in 2050, for the Netherlands. These costs are excluding the costs of electricity transmission grid reinforcement.

The study by Element Energy noted that the most significant uncertainties with regard to the annual cost of the electric heat pump pathway were the device capital investment cost, which caused the widest fluctuations in annual cost of the pathway, the costs to reinforce the electricity transmission grid, and the varying costs of electricity production, leading to varying electricity tariffs. [62]

In the present study, the annual cost of the electric heat pump pathway in 2050 reduced by 19 – 25% under the low device capital investment cost assumption, when compared to the annual costs under the high device capital investment cost assumption for electric heat pumps in 2050. Also, in the present study, the electric heat pump pathway has sensitivities of 0.15 to the electricity tariffs, and 0.37 – 0.42 to the cost of electricity transmission grid reinforcement, assumed to add 2 cents/kWh to the electricity tariffs in the present study in 2050.

The uncertainties identified in the present study have also been mainly the device capital investment costs of air and ground source heat pumps in 2050 in the Netherlands, which show wide variations in literature. The other uncertainties in the study which have the greatest effect of final annual cost of the electric heat pump pathway are the grid strengthening costs, which have not yet been studied widely in the Netherlands, to the writer's knowledge, and the electricity tariffs, which are based on varying levelized system costs of various 100% renewable energy systems modelled for Europe and worldwide for 2050 and carry significant uncertainties.

7.6.2 Comparison of Costs of Hybrid Heat Pumps with Other Studies

In the Imperial College study it was found that similar to electric heat pumps, the system costs of the hybrid heat pump scenario were comprised mainly of capital costs. [5] In the present study, along with 100% renewable electricity generation in 2050 in the Netherlands, it is also assumed that hydrogen for the hybrid pathway will be produced by electrolysis using renewable electricity (green hydrogen produced by offshore wind turbine installations in the North Sea). As such, it is the system capital costs (cost of renewable energy generation) which will decide both the electricity tariff as well as the hydrogen tariff, which, in turn, heavily influence the annual cost of the hybrid pathway for 2050.

The annual cost of the hybrid pathway in 2050 in the present study was found to increase by 3.23 billion euros (from Table 7.11) in the high energy tariff scenario, as compared to the situation with low energy tariffs, thus the annual cost of the hybrid pathway is also heavily dependent on the system capital costs, as the electricity and hydrogen tariffs are mainly decided by the capital costs of generation and production. The annual costs of the hybrid heat pump pathway in 2050 were also found to be more sensitive to variations in the hydrogen tariff, than variations in the electricity tariff.

The study by Element Energy [62] assumed that hybrid-gas heat pumps would be used in the UK, as opposed to hybrid-hydrogen heat pumps assumed in the present study. The Element Energy study did however include the cost of carbon emissions and the cost of carbon capture and storage to reduce emissions levels to the desired targets, making it a fair comparison with the present study. Hybrid-gas heat pumps do not differ from hybrid-heat pumps in operation. The study noted that utilizing hybrid heat pumps would avoid the costs of electricity transmission grid reinforcement, as the gas (or hydrogen in the present study) boiler component can cover demand exclusively during peak demand.

Similar to all electric heat pumps, the Imperial College study found that the overall annual system costs also depended on the costs of financing, or the discount rate, as mentioned in the study. The annual costs increase with increasing discount rate assumed, arising from increases in capital expenses in the energy system. The study also noted that annual system costs reduced with device capital investment cost. [5] The study by Element Energy in [62] noted that the main uncertainties of the hybrid heat pump pathway are the uncertainties in reduction of device capital investment cost of hybrid-gas heat pumps by 2050, and the uncertainties in performance.

In the present study, it was found that the annual costs of the hybrid pathway reduced with the discount rate, because of lower annual device capital investment costs and lower renovation costs. From the various literature sources analysed in the present study, investment cost reductions by 2050 for hybrid heat pumps in the Netherlands are between 30% and 33%, with 30% having been taken as the cost reduction assumption by 2050 in the present study. The main uncertainty identified in the present study is the hydrogen tariffs, which are based on the assumption of the existence of a full, mature hydrogen economy by 2050, leading to competitive hydrogen tariffs, with hydrogen production cost figures for 2050 from various literature sources used as the basis, and which vary by 3.2 cents/kWh for 2050. The other uncertainty for the annual cost of the hybrid scenario in 2050 in the present study is in the discount rate, (or the cost of financing in the Imperial College study), a higher discount rate would lead to higher annual device capital investment costs, and higher annual household renovation costs for households of insulation label E, F and G undergoing renovations to improve their insulation label to D.

7.6.3 Comparison of Costs of Hydrogen Boilers with Other Studies

In both, the Imperial College study and the study by Element Energy, it was seen that the system capital cost was a major component of the total system cost for the UK in 2050, when using hydrogen boilers to supply residential heating demand. [6][62] In the present study, it was found that the overall annual cost of the hydrogen pathway is highly sensitive to the hydrogen tariffs – with sensitivities of 0.68 – 0.78 to the hydrogen tariffs in 2050. The hydrogen tariffs are mainly comprised of the capital cost of the electrolysers and the capital cost of the offshore wind turbines used to generate the electricity. Thus, the capital costs of the renewable energy generation system are an important component of the total annual cost of the hydrogen pathway for the Netherlands in 2050.

The Imperial College also noted that the annual cost of the hydrogen pathway depended on the device capital investment costs. The study by Element Energy [62] noted that device capital investment costs played a role in the annual cost of the hydrogen pathway, but they were not as significant as in the hybrid or electric cases as hydrogen boilers were assumed to have the same installed costs in 2050 as current gas boilers in the UK. Since a similar assumption is used in the present study regarding hydrogen boilers for use in the Netherlands in 2050.a similar conclusion can be drawn for the present study.

Both, the Imperial College study and the Element Energy study ([6] [62]) note that the greatest uncertainty in the hydrogen scenario is the hydrogen tariff of 2050. In the present study, annual costs for 2050 in the hybrid scenario show sensitivities of up to 0.78 with the hydrogen tariffs, giving a wide variation in annual cost of the hydrogen pathway. The other uncertainties noted in [62] regarding the hydrogen pathway was the safety aspects related to supplying hydrogen for household heating and the public acceptance of this heating option.

As with electric and hybrid heat pumps, the cost of the hydrogen pathway was also seen to be sensitive to the discount rate used. In the Imperial College study, the discount rate was noted to substantially change the annual cost of the hydrogen pathway. Another factor investigated in the Imperial College study was the production route of hydrogen – it was found that the green hydrogen production route from renewable electricity had the highest annual costs amongst all the scenarios. [6] The present study for the Netherlands only considers costs to the consumer at the household level, and 100% green hydrogen. System interactions and the costs arising from them cannot be investigated in the present study.

7.7 Shortcomings in Research Methodology

In the present study, several assumptions have been made in order to calculate the total annual cost per decarbonisation pathway. There is a great deal of uncertainty regarding these assumptions, as they have been made for a future energy system. The assumptions for the cost of the future renewable energy generation system, the energy tariffs and the cost of grid strengthening have been taken as simple cost inputs based on literature and the costs of each decarbonisation pathway vary widely based on the specific assumptions used per scenario.

The calculation of annual space heating demand per dwelling is based on the method outlined by Kemna et al. [31] For the building volume and surface area, representative building areas and volumes were used from the Kemna study, and building average floor areas were taken from the Kemna study, and when available, from CBS Statline. The method of calculation in the present study only takes into account the heating season of the Netherlands in 2050 in terms of total number of hours, and assuming that the entire floor area of the dwelling is to be heated throughout the heating season. This provides a first order estimate of annual space heating demand per dwelling, from a national standpoint. In reality, however, different rooms in the dwelling are heated for different lengths of time through the day during the heating season – this behavioural factor is not accounted for in the present study.

The calculation methods used in this study are not based on time-dependent transient energy system models, and so the quantity of electricity and hydrogen storage required cannot be calculated for the present study, for the Netherlands in 2050. However, the system levelized cost estimates for the 100% electricity generation system of 2050 from literature include the levelized cost of electicity storage, along with the levelized cost of electricity transmission and curtailment. The estimates for the levelized cost of hydrogen storage from [59] are comparable to the levelized hydrogen production cost estimates from other sources, which would lead to hydrogen storage energy prices being comparable to the hydrogen tariff estimates for 2050 used in the present study. This can be assumed to be true as long there is a fully mature hydrogen economy in the Netherlands by 2050, as has been assumed in the present study.

For the electric scenario, the increase in heat pump deployment is assumed to lead to an increase in electricity tariffs by 2 cents/kWh. Other studies in the past have studied this effect of increased heat pump deployment, and studied the resulting increase in peak load. These studies have not, however, correlated the increase in peak electricity requirement with the possible resulting increase in electricity tariffs. The increase in electricity tariffs would depend on the increase in renewable energy generation capacity required, and the technologies used to increase flexibility and strengthen and expand the grid. [63] Also mentions similar price ranges for transmission grid reinforcement costs, but this presents another source of uncertainty.

The costs have been calculated for the year 2050, assuming the 100% renewable energy generation system, and the fully mature hydrogen economy already exist in the Netherlands in 2050. Costs have not been calculated in a transitional manner from 2020 to 2050. Such transition modelling requires whole energy systems models such as the ones used by Imperial College. Similar studies to the Imperial College study have not been performed in a Dutch context as yet. For the Netherlands, modelling software such as VESTA MAIS can model the entire Dutch residential heating grid, however, it does not have cost inputs for hydrogen injection into the gas grid, the costs of upgrading the gas grid to support hydrogen, or database values for hydrogen production costs, transport and storage costs, etc, which are all required in order to perform a study of pathway transitions from 2020 to 2050.

Another drawback is the 'pathway' approach, which is highly dependent on initial assumptions that are seen to have large uncertainties in them. The comparison is black-and-white, comparing the cost of adopting each decarbonisation technology over the entire housing stock of 2050. In reality, it is likely that there will be a combination of solutions used, in order to minimize investments in changes to the current electricity and heat infrastructure of the Netherlands, and to increase the flexibility of operation of the energy system of 2050. Modelling these combined technical scenarios for 2050 poses similar challenges as whole energy system modelling, explained earlier for the VESTA MAIS model for the built environment of the Netherlands. The lack of continuous learning ability due to the lack of whole-energy-system models that include green hydrogen production and hydrogen devices at end user-sites of any kind, is another drawback of the 'pathway' approach in the present study and cost developments for device capital investment and household renovation cannot be studied in the period 2020 - 2050.

The lack of whole-energy-system modelling ability also presents a barrier to analysing the option of using heat grids to decarbonise the residential heating sector of the Netherlands by 2050. Currently, residential space heat production of the Netherlands is decentralised, with heat being produced at the consumer site, and natural gas being transported by pipelines to buildings. Centralised heat grids are not widespread in the Netherlands, their costs come with greater uncertainties than the costs for electric and hybrid heat pumps, particularly with respect to developing he centralised heat grid. For these reasons, the heat grid pathway was excluded from the present study.

The present study also does not explore the impact of cooking on the domestic energy requirements as the main aim of the present study was to study the cost involved in decarbonising the residential space heating demand (and domestic hot water demand which is the second-most dominant use of natural gas in current Dutch households, after space heating). According to [35], cooking accounts for less than 4% of the annual household natural consumption on average, per household, in the Netherlands. The effect of neglecting the cooking demand on hydrogen or electricity consumption is not expected to be significant. Considering cooking would also require the consideration of the investment cost per household for hydrogen cookers in the hydrogen and hybrid pathways, and electric cookers for the electric pathway, which would add to annual costs in all three pathways.

Finally, the option of using hydrogen fuel cells at households to satisfy space heating demand. Fuel cells can be used to provide energy for the household in the form of a Combined Heat and Power (CHP) system such as the Viessmann Vitovalor. [67] The fuel cell utilises electricity to produce hydrogen, which produces heat as a by-product. The waste heat is harnessed through heat exchangers, which then provide space heat, and also heat for domestic hot water demand. The system by Viessmann in [67] is sized for the energy demands of a detached home in the UK. According to [68] the systems cost from £12000 to £17000 (13200 – 18700 euros). However, unlike with hydrogen boilers, no studies in the UK or in the Netherlands were found that were performed using hydrogen fuel cells for household energy generation and heating, as such, there is a lack of availability of data for cost predictions of fuel cells in the Netherlands by 2050. For this reason, the study of fuel cells was neglected in the present study.

8. Scenario Study for Uncertainties of Model Inputs

The energy system of the Netherlands in 2050 is assumed in the present study to be comprised of 100% renewable energy generation capacity for electricity and hydrogen. Electricity is assumed to be produced from solar photovoltaics, wind turbines and other renewable energy technologies. Energy storage such as battery storage, and flexibility technologies are also assumed to exist, to cover for mismatches between renewable energy supply, and final energy demand. Residential heating in 2050 is achieved through either electric air and ground source heat pumps, hybrid-hydrogen heat pumps, or end-use hydrogen boilers. The devices differ on the basis of initial investment cost and annual energy cost.

From the previous chapters, we have seen that the annual cost of each pathway is heavily dependent on the initial assumptions used. For electric air and ground source heat pumps, the greatest uncertainties to final annual cost per pathway lie in the device capital investment costs by 2050, the costs of transmission grid reinforcement in 2050 and the electricity input tariff range. For the hybrid pathway. The greatest uncertainty in determining annual cost per pathway was the extent of price reductions by 2050, and the hydrogen tariff range for 2050. For the hydrogen boiler scenario, the greatest uncertainty lies in the hydrogen tariff range for 2050.

In order to reduce uncertainties in the results in the present study, six scenarios have been constructed by 2050 based on the results of chapters 5, 6 and 7 in this report. For all scenarios, cost reduction factor of 0.75 is applied to household renovation costs for insulation label improvement by 2050, and factor of 0.8 is applied to low temperature radiators. Discount rate of 4% is used, based on [64], [65] and [66]. Grid reinforcement costs are included in the electricity tariffs for the electric heat pump scenario only as hybrid heat pumps can use the hydrogen boiler component to cover peak load exclusively, as found in [62].

8.1 Scenario Outline

The energy system of the Netherlands in 2050 in all scenarios is assumed in the present study to be comprised of 100% renewable energy generation capacity for electricity and hydrogen. Electricity is assumed to be produced from solar photovoltaics, wind turbines and other renewable energy technologies. Energy storage such as battery storage, and flexibility technologies are also assumed to exist, to cover for mismatches between renewable energy supply, and final energy demand. For the hybrid and hydrogen scenarios, dedicated hydrogen production facilities are assumed to produce 100% green hydrogen in the Northern Netherlands via electrolysis from electricity produced by offshore wind turbine installations in the North Sea in 2050.

Residential heating in 2050 is achieved through either electric air and ground source heat pumps, hybrid-hydrogen heat pumps, or end-use hydrogen boilers. The devices differ on the basis of initial investment cost and annual energy cost. For all scenarios, cost reduction factor of 0.75 is applied to household renovation costs for insulation label improvement by 2050, and factor of 0.8 is applied to low temperature radiators. Discount rate of 4% is used.

The scenarios are selected to cover the range of device capital investment cost estimate range of air and ground source heat pumps from literature (divided into 'high' capital investment scenarios and 'low' capital investment scenarios), and the range of electricity and hydrogen tariff inputs for 2050 from system cost estimates of various studies for 100% renewable energy generation grids in Europe, divided into 'low', 'moderate' and 'high' tariffs – these are detailed in Table 8.1.

- Scenario 1: High device capital investment costs, low electricity tariffs, high hydrogen tariffs
- Scenario 2: High device capital investment costs, moderate electricity tariffs and hydrogen tariffs
- Scenario 3: High device capital investment costs, high electricity tariffs, low hydrogen tariffs

- Scenario 4: Low device capital investment costs, low electricity tariffs, high hydrogen tariffs
- Scenario 5: Low device capital investment costs, moderate electricity tariffs and hydrogen tariffs
- Scenario 6: Low device capital investment costs, high electricity tariffs, low hydrogen tariffs

Table 8.1 – Assumptions for Each Scenario for 2050

Scenario	Electricity Tariffs (euros/kWh)	Hydrogen Tariffs (euros/kWh)	Device Capital Investment Costs (2050) (euros/m^2)	Reduction of capital investment costs by 2050 with respect to current costs (%)
Scenario 1	Electric Pathway – 0.101 Hybrid pathway – 0.081	0.078	ASHP – 66 GSHP – 77 HHP – 27 HB – 9	ASHP – 17 GSHP – 17 HHP - 25
Scenario 2	Electric Pathway – 0.126 Hybrid pathway – 0.106	0.060	ASHP – 66 GSHP – 77 HHP – 27 HB – 9	ASHP – 17 GSHP – 17 HHP - 25
Scenario 3	Electric Pathway – 0.154 Hybrid pathway – 0.134 euros/kWh	0.046	ASHP – 66 GSHP – 77 HHP – 27 HB – 9	ASHP – 17 GSHP – 17 HHP - 25
Scenario 4	Electric Pathway – 0.101 Hybrid pathway – 0.081	0.078	ASHP – 25 GSHP – 49 HHP – 24 HB – 9	ASHP – 33 GSHP – 27 HHP - 30
Scenario 5	Electric Pathway – 0.126 Hybrid pathway – 0.106	0.060	ASHP – 25 GSHP – 49 HHP – 24 HB – 9	ASHP – 33 GSHP – 27 HHP – 30
Scenario 6	Electric Pathway – 0.154 Hybrid pathway – 0.134	0.046	ASHP – 25 GSHP – 49 HHP – 24 HB – 9	ASHP – 33 GSHP – 27 HHP - 30

8.2 Annual Cost of Each Scenario

The annual cost per scenario has been calculated using the same methodology as used in the previous sections of this report. The results are given separately for high investment cost scenarios and the low investment cost scenarios. Scenario 4 is presented separately as the results differ from the results of the other 5 scenarios, which are fairly uniform. The scenarios in this chapter are mainly designed to account for the variability of device capital investment cost assumptions for electric and hybrid heat pumps in 2050, and the variation in the electricity and hydrogen tariff assumptions for 2050 used in the present study. The same discount rate of 4%, and the same cost reduction factors for household renovation and low temperature radiators (electric and hybrid pathways) have been used to minimize the effect of these uncertainties on the annual cost per pathway for each scenario.

8.2.1 Annual Cost per Pathway for Scenarios 1, 2 and 3

The results of the scenario study are given in Table 8.2. From the table, it is seen that under the high investment cost scenarios, namely Scenario 1, Scenario 2 and Scenario 3, the hydrogen boiler pathway has the lowest annual costs, at 8.10 – 11.92 billion euros, in 2050. The electric heat pump pathway is the most expensive in all three scenarios, with annual costs of 14.41 – 16 billion euros annually. The hybrid pathway is cheaper than the electric heat pump pathway in all three scenarios, with annual costs of 11.24 – 13.54 billion euros.

8.2.2 Annual Cost per Pathway for Scenarios 5 and 6

Under the low investment cost scenarios, (Scenarios 4, 5 and 6), the hydrogen boiler pathway is the cheapest in Scenarios 5 and 6 (moderate and low hydrogen tariffs, respectively), with annual costs of 8.10 – 9.77 billion euros annually (the costs for the hydrogen scenario do not change in the low investment cost scenarios, compared to the high investment cost scenarios). For scenarios 5 and 6, the electric heat pump pathway is the most expensive, with annual costs of 12.40 – 13.37 billion euros (moderate and high electricity tariffs respectively). The hybrid pathway is cheaper than the electric pathway in Scenarios 5 and 6, with annual costs of 10.94 – 11.91 billion euros annually.

8.2.3 Annual Cost per Pathway for Scenario 4

In Scenario 4, the low investment cost, low electricity tariff, and high hydrogen tariff scenario for 2050, the electric heat pump pathway has the lowest annual costs, at 11.49 billion euros annually. The hydrogen pathway (high hydrogen tariffs) has annul costs of 11.92 billion euros. The hybrid pathway has the highest annual costs per pathway in this scenario, with annual costs of 13.25 billion euros. This scenario represents the lowest electricity tariff estimate from the range of electricity tariffs used in the present study for 2050 (including grid strengthening costs for the electric heat pump scenario in the electricity tariffs for 2050, and excluding the grid strengthening costs or hybrid heat pumps, as explained earlier in this report).

For the hybrid pathway, the device capital investment costs are almost the same as those of electric air source heat pumps. In Scenarios 4, 5 and 6, it was found that mostly air source heat pumps would be used (8 million air source heat pumps in 8 million dwellings, out of the assumed 9 million in 2050), making the cumulative device capital investment cost over all dwellings in the electric scenario only slightly higher than the hybrid scenario in 2050. The electric heat pump component is assumed to meet between 60 – 90% of the total annual space heating demand (hot water demand met entirely by the hydrogen boiler component) and so the volume of fuel (electricity in the electricity pathway, electricity + hydrogen in the hybrid pathway) used annually is greater for the hybrid pathway compared to the electric pathway, with 10 – 40% of the annual fuel costs per household comprised of hydrogen fuel cost. Thus, fuel costs are higher for the hybrid pathway compared to the electric pathway.

Hydrogen fuel cost is of importance in the hybrid scenario, as the combustion of hydrogen has efficiencies of < 1 (assumed to be 0.97 of Higher Heating Value of Hydrogen in the present study), whereas the conversion of electricity to heat, by virtue of the conversion of energy from high-grade (electricity) to low-grade (heat), efficiencies of > 1 (as in, the Coefficient of Performance) can be achieved. The volume of fuel used is higher when combusting hydrogen, than when converting electricity to heat. As such, when the hydrogen tariff is assumed to be high in 2050 (the maximum hydrogen tariff estimate for 2050 in the present study) and the electricity tariffs are assumed to be the minimum from the electricity tariff estimates of 2050 used in the present study, the hybrid pathway has higher costs than the electric heat pump pathway.

For the hydrogen boiler pathway, device capital investment cost assumptions for 2050 are much lower than in the electric heat pump pathway. For houses running hydrogen boilers, renovation costs (for households of insulation label E, F and G renovated to label D) and fuel costs (households of all insulation labels) are the main annual costs per household, and consequently, per pathway. The renovations assumed in the hybrid and hydrogen scenarios are less extensive than the renovations assumed in the electric heat pump pathway, where all households of insulation quality D and lower are assumed to be renovated to insulation label C. Another assumption was that renovations would only be performed on households in the hybrid and hydrogen scenarios if they led to a decrease in annual cost per household in 2050. The renovation costs only reduce annual cost per pathway in the hybrid and hydrogen pathways, compared to the situation of no renovations performed.

Due to the higher volume of energy used annually in the hydrogen pathway compared to the electric heat pump pathway in 2050, and the situation of high hydrogen tariffs combined with low electricity tariffs in 2050 in Scenario 4, the annual cost of the hydrogen boiler pathway is slightly higher than the annual cost of electric heat pump pathway. Also, annual energy expenses per household in 2050 of the hybrid pathway lie in between the annual energy expenses per household in the hydrogen pathway, and the annual energy expenses per household in the electric pathway. The hydrogen boilers are assumed to have much lower device capital investment costs than hybrid heat pumps in this scenario (and all scenarios), these higher investment costs are mainly what make the hybrid pathway more expensive than the hydrogen pathway in scenario 4.

Table 8.2 – Results of Scenario Study for 2050

Scenario	**Pel (electric) (€/kWh)**	**Pel (hybrid) (€/kWh)**	**PHyd (€/kWh)**	**Electric**	**HHP**	**HB**
Scenario 1	0.101	0.081	0.078	Billion EUR 14.41	Billion EUR 13.54	Billion EUR 11.92
Scenario 2	0.126	0.106	0.060	Billion EUR 15.16	Billion EUR 12.20	Billion EUR 9.77
Scenario 3	0.154	0.134	0.046	Billion EUR 16.00	Billion EUR 11.24	Billion EUR 8.10
Scenario 4	0.101	0.081	0.078	Billion EUR 11.49	Billion EUR 13.25	Billion EUR 11.92
Scenario 5	0.126	0.106	0.060	Billion EUR 12.40	Billion EUR 11.91	Billion EUR 9.77
Scenario 6	0.154	0.134	0.046	Billion EUR 13.37	Billion EUR 10.94	Billion EUR 8.10

9. Summary

This section of the report provides a summary of the methods applied, and the results obtained in the present study. The context of the present study is the increasing need for the Netherlands to reduce carbon dioxide and other greenhouse gas emissions in every sector of production, in order to meet the terms of international climate agreements, and to create an energy system that is 100% renewable by the year 2050.

The built environment of the Netherlands is a large source of greenhouse gas emissions and there several possibilities for reducing the emissions from the built environment to zero by the year 2050. The aim of the present study was to explore three alternative technologies, or three decarbonisation pathways, to the current method of space heating in the Netherlands which will not use natural gas for heating – electric heat pumps, hybrid heat pumps, and hydrogen boilers. The study aims to find out which alternative heating method, or decarbonisation technology, could be implemented with the least social cost, and the factors that system cost relies on, in each pathway.

The cost of each pathway has been calculated by taking into account the annual space heating requirements of each type of dwelling in the Netherlands in 2050 from daily meteorological data with increases in average daily temperature by 2050 with respect to current temperatures taken into account and the physical dimensions of each dwelling type, and calculating the annual energy cost per household based on electricity and hydrogen tariffs as charged to the end users in households. Annual cost of heating per household is a function of the annual space heating demand per dwelling, and the efficiency or coefficient of performance of hydrogen boilers, and electric and hybrid heat pumps respectively.

The method of calculating the annual space heating demand is a widespread one, used across Europe, to calculate building HVAC loads. This method does not include the domestic demand for hot water, which is relatively constant through the year. The domestic hot water demand is calculated for each type of dwelling, based on the relatively constant (relative to the space heating demand) average daily hot water demand per person in 2050, taken from literature, and the number of people per dwelling type, based on average figures by EPA. While the space heating demand is assumed to be only during the heating season, domestic hot water demand is taken to be over the entire year.

Total annual costs per household in 2050 are taken as the sum of the annual energy cost per household, and the annual investment and maintenance costs per household in 2050. Annual investment costs are assumed to include the cost of improving household insulation levels, the cost of low temperature radiators in the electric and hybrid pathways, and the cost of disconnecting from the gas grid in the electric pathway in the present study. Investment and maintenance costs of each device have been annuitized in the present study, over the lifetime of each device (15 years), having been taken from various sources in existing literature. Insulation costs have been annuitized over the lifetime of the building insulation (50 years).

There is also a great deal of uncertainty regarding electricity and hydrogen tariffs in 2050. In Chapter 5, it is seen that the annual cost per pathway of the electric scenario is not as sensitive to the energy tariffs as the annual costs per household in the hybrid and hydrogen boiler pathways. The device capital investment cost figures for 2050 for electric and hybrid heat pumps also have considerable uncertainty in their estimates, which are seen to have a large effect on total annual cost per household, in Chapter 5. It is also found in Chapter 5, that the annual costs per household in the electric heat pump scenario were also quite sensitive to the costs of the low temperature radiators, and to the cost of household renovations by 2050.

To calculate the total cost per decarbonisation pathway, changes in the number of dwellings by 2050 in the Netherlands need to be accounted for. Housing projections by organisations such as TNO indicate that the Dutch housing stock will rise to 9 million dwellings by 2050, from 7.8 million dwellings at present. For the present study, it has been assumed that all dwellings will be occupied, in the year 2050.

The total annual cost of each decarbonisation pathway is the sum of the total annual cost per household for all 9 million houses in the Netherlands. In Chapter 6, it is seen that the electric heat pump pathway has the highest annual costs amongst all three decarbonisation pathways, hydrogen boilers have the lowest annual costs per pathway in 2050.

Because of the uncertainties regarding the future energy system, sensitivity analysis of the annual cost per pathway is performed in Chapter 7. The annual costs per pathway are tested for sensitivity of annual cost per pathway to device capital investment costs, discount rate used, sensitivity of the annual cost of the hybrid pathway to the electricity tariff alone (by assuming that electricity transmission grid reinforcement will lead to an increase in electricity tariff in 2050 in the electric and hybrid pathways), sensitivity of annual costs to the hydrogen tariff alone, and sensitivity to household renovations performed on households in the hydrogen and hybrid scenarios. The uncertainties that will have the biggest impact on annual cost estimates per pathway for 2050 are identified as the device capital investment cost, and the electricity and hydrogen tariffs of 2050.

Based on the results of chapters 5, 6 and 7, scenarios are constructed for the year 2050 in the Netherlands, to account for the variability in the device capital investment cost, and the variation in electricity and hydrogen tariffs. The hydrogen boiler pathway is found to have the least annual cost in 2050 in 5 out of the 6 analysed scenarios. In each of these five scenarios, the hybrid pathway is cheaper than the electric pathway. The electric pathway is the cheapest in Scenario 4, under low electricity tariffs, low capital investment cost of heat pumps, and high hydrogen tariffs. The difference in annual cost per pathway between the hydrogen pathway and the electric pathway in Scenario 4 is found to be less than 5%.

10. Conclusions

In order to offset the emissions of the residential housing sector of the Netherlands in accordance with its climate agreements and to prevent further damage due to global climate change, the Netherlands will have to completely decarbonise its residential heating sector by the year 2050. There are several pathways to achieve total decarbonisation of the residential heating sector of the Netherlands in 2050 that rely on different devices to meet annual residential heating demand. The study aims to answer the questions –

- What are the ways through which the residential heating sector of the Netherlands can be decarbonised?
- Which decarbonisation pathway could be achieved with the least cost to the end-user?
- What factors do the system cost rely on?
- What are the uncertainties regarding the annual cost of each pathway, and what are their impacts on overall cost?

Three decarbonisation technologies have been investigated in the present study – all-electric heat pumps, hybrid heat pumps and end-use hydrogen boilers. The technologies differ in their operation, the fuel they use to provide heat, their investment and maintenance costs, and their efficiencies. The final annual cost per decarbonisation pathway is the total of the annual investment and maintenance cost of each device per household, the annual cost of heat per dwelling (including domestic hot water, excluding cooking), the cost of improving household insulation levels, and the cost of reinforcing the national electricity transmission grid to accommodate increased renewable energy generation and peak electricity load due to electrification of heat.

The annual costs per household for each decarbonisation technology are mainly dependent on the annual space heating demand per dwelling in 2050, and show a high level of sensitivity to electricity and hydrogen tariffs (which are based on system capital costs for the renewable energy generation system of the Netherlands in 2050) and the investment (device capital investment cost, household renovations to improve insulation levels, low temperature radiators for electric and hybrid heat pumps) and maintenance costs of each device.

The total annual cost per pathway are also particularly sensitive (amongst the three decarbonisation technologies in the present study) to the device capital investment cost assumptions in the electric heat pump scenario, which carry a high level of uncertainty up to 2050. The high device capital investment costs and higher renovation costs in the electrical pathway compared to the hybrid and hydrogen pathways, are the main reasons for the annual costs of electric heat pumps being higher than the other two pathways; electric heat pumps have the lowest energy costs once household insulation levels are adequate.

All three pathways show a high sensitivity to the electricity and hydrogen tariff assumptions for 2050, which also carry a high level of uncertainty, particularly hydrogen tariffs, which are estimated for GW-scale electrolysis for production, which does not exist yet, making cost estimations for 2050 highly uncertain. The annual costs of the hybrid pathway are more sensitive to hydrogen tariffs than to electricity tariffs. The hydrogen pathway shows the highest sensitivity to the hydrogen tariffs as annual costs in the hydrogen boiler pathway are comprised mainly of annual hydrogen fuel costs for heating.

Other uncertainties are the costs of reinforcing the electricity transmission grid, the cost reduction of household renovations and low temperature radiators by 2050 compared to their current costs, and the discount rate used for annuitizing the investment costs in each scenario in 2050. The hybrid and hydrogen pathways also show sensitivity to renovation costs if household insulation in improved in these pathways. The necessary extent of renovation is not as deep as it is for electric heat pumps. The electricity transmission grid would not require reinforcement if hybrid heat pumps are used as hydrogen boilers can cover peak demand exclusively, lowering annual costs of the hybrid pathway relative to the electric heat pump pathway.

To account for the uncertainties in investment costs and energy tariffs by 2050, six scenarios were constructed to account for their variation, ranging from low investment cost scenarios to high investment cost scenarios. Discount rate of 4% per year is used, and cost of home renovations is assumed to reduce by 2050 compared to present-day costs. The hydrogen boiler pathway is the cheapest decarbonisation pathway in five of these scenarios, with the electric heat pump pathway being the most expensive pathway in each of the five scenarios in 2050. In one of scenarios, electric heat pumps are the cheapest, annually, in 2050. This is under the low investment cost, low electricity tariff (the minimum electricity tariff from the range of tariff estimates by 2050), and high hydrogen tariff (the maximum hydrogen tariff from the range of tariff estimates for 2050). The hydrogen pathway was found to be more expensive than the electric pathway by less than 5%.

References

[1] Folckert van der Molen (2018), "Technisch en Economisch Potentieel Aardgasvrije Gebouwde Omgeving Drechtsteden", The Hague: PBL.

[2] Ruud van den Wijngaart, Steven of Poland, Bas van Bemmel and Miriam Harm Link (2018), "Potentieel en Costen Klimaatneutrale Gebouwde Omgeving Gemeente Utrecht", The Hague: PBL.

[3] A. van den Noort, W. Sloterdijk, M. Vos, "Verkenning waterstofinfrastructuur" (November 2017), Report No. OGNL.151886, Rev. 2, for Ministerie van Economische Zaken, Netherlands

[4] Fuel Cells and Hydrogen 2 Joint Undertaking Tech. Rep. 2019. DOI: 10.2843/341510

[5] J. Sijm, L. Beurskens, M. Marsidi, R. Niessink, M. Scheepers, K. Smekens, A. van der Welle, H, de Wilde, (2020) "Review of energy transition scenario studies of the Netherlands up to 2050" (February 2020) TNO Report, TNO 2019 P12095, Project No. 060.34020 (Integrated Energy Systems Analysis) and 060.38214 (Sustainable Energy Scenarios)

[6] G. Strbac, D. Pudjianto, R. Sansom, P. Djapic, H. Ameli, N. Shah, N. Brandon, A. Hawkes, "Analysis of Alternative UK Heat Decarbonisation Pathways" (August 2018), Imperial College, UK

[7] Ram M., Bogdanov D., Aghahosseini A., Gulagi A., Oyewo A.S., Child M., Caldera U., Sadovskaia K., Farfan, J., Barbosa LSNS., Fasihi M., Khalili S., Dalheimer B., Gruber G., Traber T., De Caluwe F., Fell H.-J., Breyer C. "Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors". Study by Lappeenranta University of Technology and Energy Watch Group, Lappeenranta, Berlin, March 2019.

[8] Schlachtberger, D., Brown, T., Schramm, S., &; Greiner, M. (2017). "The benefits of cooperation in a highly renewable European electricity network". Energy, 134, 469-481. doi:10.1016/j.energy.2017.06.004

[9] Jacobson et al., Joule 1, "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World" 108–121 September 6, 2017 (2017) Elsevier Inc. http://dx.doi.org/10.1016/j.joule.2017.07.005

[10] B. Bekhuis. (2018). "The role and potential of a hybrid heat pump in an existing Dutch house", MSc Thesis, Eindhoven Technical University

[11] M. Berger, D. Radu, K. Ryszka (2020) "The Role of Hydrogen in the Dutch Electricity System" Technical Report

[12] CBS. (2020). Statline Database. "Energy Prices - Natural Gas and Electricity, Average Price for End Users" URL: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81309NED/table?ts=1595857223165

[13] Energiemarketinformatie.nl. (2020) URL: https://www.energiemarktinformatie.nl/beurzen/elektra/

[14] CBS. (2020). Statline Database. "Energy Consumption by Sector – Energy Consumption in Private Homes; Housing Types and Regions" URL: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?ts=1595858680927

[15] CBS. (2020). Statline Database. "Natural gas and electricity, average prices of end users" URL: https://opendata.cbs.nl/#/CBS/nl/dataset/81309NED/table?ts=1597076575528

[16] Government.nl (2020) URL: https://www.government.nl/topics/environmental-taxes/energy-tax

[17] NCM (2019) "Low Temperature Heating, Technical documents", URL: https://www.ncm-pcdb.org.uk/sap/lowtemperatureheating

[18] R. Hermkens, S. Jansma, M. van der Laan, H. de Laat, B. Pilzer, K. Pulles (2018) "Toekomstbestendige gasdistributienetten", July 5, 2018, KIWA, GT-170272

[19] https://biogas.ifas.ufl.edu/ (2020). Under "Frequently Asked Questions" URL: https://biogas.ifas.ufl.edu/FAQ.asp#:~:text=While%20combustion%20of%20biogas%2C%20like,add%20to%20greenhouse%20gas%20emissions.

[20] J. Gigler, M. Weeda. (2018) "Outlines of a Hydrogen Roadmap" (May 2018), pp. 47 – 55, TKI Nieuw Gas

[21] TNO (2019) URL: https://www.tno.nl/en/about-tno/news/2019/3/starting-signal-for-design-of-gigawatt-electrolysis-plant/

[22] Istp.eu (Institute of Sustainable Process Technology, 2019) URL: https://ispt.eu/news/kick-off-for-designing-a-gigawatt-electrolysis-plant/

[23] G. Glenk, S. Reichelstein (2019) "Economics of Converting Renewable Power to Hydrogen", Nature Energy Vol. 4, March 2019, pp. 216 – 222

[24] W. Terlouw, D. Peters, J. van Tilburg, M. Schimmel, T. Berg, J. Cihlar, G. Ur Rehman Mir, M. Spöttle, M. Staats, A. V. Lejaretta, M. Buseman, M. Schenkel, I. van Hoorn, C. Wassmer, E. Kamensek, T. Fichter. (2019) "Gas for Climate: The optimal role for gas in a net-zero emissions energy system", (March 2019), Reference No.: 203997

[25] Hydrogen Council (2020) "Path to hydrogen competitiveness: A cost perspective" January 2020 Technical Report.

[26] A. van Wijk "The Green Hydrogen Economy in the Northern Netherlands" report for Noordlijk Innovation Board

[27] W. Mathis, J. Thornhil, (2019) BloombergNEFhttps://www.bloomberg.com/news/articles/2019-08-21/cost-of-hydrogen-from-renewables-to-plummet-next-decade-bnef

[28] IRENA (2019) "Hydrogen: A Renewable Energy Perspective" Report prepared for the second Hydrogen energy ministerial meeting, Tokyo, September 2019

[29] A. van Wijk, J. Chatzimarkakis "Green Hydrogen for a European Green Deal A 2x40 GW Initiative"

[30] S. Hers, T. Scholten, R. van der Veen, S. van de Water, C. Leguijt, F. Rooijers (2018) "Waterstofroutes Nederland Blauw, groen en import" (June 2018) with CE Delft

[31] Kemna, R., & Acedo, J. (2014). "Average EU building heat load for HVAC equipment". Final Report of Framework Contract ENER C, (August).

[32] KNMI (2014) "KNMI '14 klimaatscenario's voor Nederland" Brochure pp. 5

[33] Dutch PV Portal, (2019) Delft University of Technology, URL: https://www.tudelft.nl/ewi/over-de-faculteit/afdelingen/electrical-sustainable-energy/photovoltaic-materials-and-devices/dutch-pv-portal/meteorologisch-data-portal/

[34] K. van Dyck 'Green Walls in the Urban Netherlands', Utrecht University

[35] D. Majcen, "Predicting energy consumption and savings in the housing stock: A performance gap analysis in the Netherlands". PhD. Thesis Delft University of technology.

[36] CBS. (2020). Statline Database. "Stock houses; average area; house type, year of construction, region" URL: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82550NED/table?ts=1595710992911

[37] power-calculation.com (2020) URL: https://power-calculation.com/hot-water-heater-cost-energy-consumption.php

[38] I. Staffell. (2012) A "review of domestic heat pumps", Energy Environ. Sci., 2012, 5, 9291–9306, DOI: 10.1039/C2EE22653G

[39] D. Klip. (2017). "The transition of the residential heating system" (Rep. No. 2017 01). The Hague: CIEP.

[40] R. Niessink, (2019) Technology Factsheet – Air Source Heat Pumps, ECN, TNO

[41] R. Niessink, (2019) Technology Factsheet – Ground Source Heat Pump - Households, ECN, TNO

[42] Natural Resources Canada (2002). "Commercial Earth Energy Systems: A buyer's Guide", ISBN 0-662-32808-6, Cat. No. M92-251/2002E

[43] Smarterhouse.org (2020) URL: https://smarterhouse.org/water-heating/replacing-your-water-heater

[44] Financeformulas.net (2020) URL: https://financeformulas.net/Annuity_Payment_Formula.html

[45] Element Energy Limited. (December 2017). “Hybrid Heat Pumps Final report for Department for Business, Energy & Industrial Strategy”, UK

[46] R. Niessink, (2019) Technology Factsheet – Hybrid Heat Pumps, Households, ECN, TNO

[47] Giacomini Group (2019) Retrieved from https://www.giacomini.com/en/hydrogen-systems/h2ydrogem-hydrogen-boiler-giacomini

[48] BoilerGuide (2012) https://www.boilerguide.co.uk/hydrogen-powered-boiler-developed-by-giacomini

[49] HVACinformed.com Retrieved from https://www.hvacinformed.com/news/bdr-thermea-group-hydrogen-powered-domestic-boiler-co-1566401465-ga-co-1566401840-ga.1566402870.html

[50] Northern Gas Networks, Wales & West Utilities, KIWA, Amec Foster Wheeler. (2016) “H21” [Review of H21]. (p. 147) Leeds City Gate.

[51] Theheatinghub.co.uk (2020) URL: https://www.theheatinghub.co.uk/boiler-quote-calculator-tool

[52] B. M. Delgado, R. Kotireddy, S. Cao, A. Hasan, Pieter-Jan Hoe, J. L.M. Hensen, K. Sirén (2018) “Lifecycle cost and CO2 emissions of residential heat and electricity prosumers in Finland and the Netherlands” Energy Conversion and Management 160 (2018), pp. 495–508, https://doi.org/10.1016/j.enconman.2018.01.069

[53] B.L. Schepers, N.R. Naber F.J. Rooijers, C.Leguijt, “Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving” – Update 2016, (2016) pp.71 Publication number: 15.3A31.36

[54] M. Duijve. (2012). “Comparative assessment of insulating materials on technical, environmental and health aspects for application in building renovation to the Passive house level”, MSc Thesis, Utrecht University

[55] Reenergizeco “When to Replace Your Home Insulation” URL: https://www.reenergizeco.com/replace-home-insulation/

[56] F. Taminiau “Hydrogen admixture in the Dutch gas grid” (July 2017) TNO report in collaboration with the University of Amsterdam, pp. 8

[57] M. Mulder, P. Perey, J. L. Moraga (2019) “Outlook for a Dutch hydrogen market economic conditions and scenarios”, (March 2019) CEER Policy Papers No. 5, Centre for Energy Economics Research (CEER) and University of Groningen, ISBN: 978-94-034-1566-6 (pdf)

[58] CBS. (2016). Statline URL: https://www.cbs.nl/en-gb/news/2016/14/small-and-relatively-expensive-housing-in-amsterdam

[59] R. van Gerwen, M. Eijgelaar, T. Bosma (2019) "Hydrogen in the Electricity Value Chain" Group Technology and Research Position Paper 2019

[60] M. Weeda, R. Niessink, (2020) "Hydrogen as an option for a climate-neutral heat in existing buildings", (March 2020), TNO report, report number TNO 2020 M10028

[61] J. Love, A. Z.P. Smith, S. Watson, E. Oikonomou, A. Summerfield, C. Gleeson, P. Biddulph, L.F. Chiu, J. Wingfield, C. Martin, A. Stone, R. Lowe. (2017) "The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial", (July 2017) Applied Energy 204 (2017) 332 – 342, http://dx.doi.org/10.1016/j.apenergy.2017.07.026

[62] Element Energy, E4Tech, (2018) "Cost analysis of future heat infrastructure options" (March 2018) Report for National Infrastructure Commission, UK

[63] Carbonbrief.org (2017) URL: https://www.carbonbrief.org/in-depth-whole-system-costs-renewables

[64] J. Hu, R. Harmsen, W. Crijns-Graus, E. Worrell (2018) "Barriers to investment in utility-scale variable renewable electricity (VRE) generation projects", Renewable Energy 121 (2018) 730-744, https://doi.org/10.1016/j.renene.2018.01.092

[65] M. van der Boomen, R. Schoenmaker, J.Verlaan, R. Wolfert (2017) "Common misunderstandings in life cycle costing analyses and how to avoid them" , Delft University of Technology (2017) Published in Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure DOI 10.1201/9781315375175-251

[66] J. Steinbach, D Staniaszek (2015) "Discount rates in energy system analysis Discussion Paper" Commissioned by the Buildings Performance Institute Europe (BPIE), May 2015

[67] Viessmann Vitovalor "Brochure for Homeowners" Retrieved 20 August 2020 URL: https://cdn0.scrvt.com/2828ebc457efab95be01dd36047e3b52/611c5211e315ee84/3ea3f3919a7c/Vitovalor---Enduser.pdf

[68] ChapmanPlumbers.com (2020) Retrieved on 20 August 2020 URL: https://www.chapmanplumbers.com/heating-services/fuel-cell-technology-vitovalor/#:~:text=The%20Vitovalor%20300P%20price%20varies,a%20new%20heating%20system%20anyway.

Appendix – Higher Heating Value vs. Lower Heating Value

In combustion processes, there are two ways to calculate the efficiency – based on the higher heating value of the fuel, or based on the lower heating value. In combustive reactions that involve hydrogen-rich fuels (such as methane) or hydrogen, water is often produced as a by-product (in hydrogen combustion with oxygen, water is the only product of combustion, besides heat). The water that is produced in the reaction chamber then gets converted to vapour by the heat of combustion, causing a loss in energy available to do work. The amount of energy lost in the process is equal to the latent heat of vaporization of water.

If the water vapour is released as exhaust fumes directly, the loss of heat of combustion is irreversible and fuel efficiencies under these circumstances should be calculated using the Lower Heating Value. However, if the water vapour is recirculated and condensed using a heat exchanger, a large quantity of the latent heat of vaporization can be recovered, lowering the losses to heat of combustion. In such circumstances, the efficiencies should be calculated on the basis of the Higher Heating Value of the fuel. In the Netherlands, the majority of household central heating gas boilers are condensing boilers.

In the present study, hydrogen boilers are to cover partial (hybrid pathway) or total (hydrogen boiler pathway) annual space heating demand, and cover total annual domestic hot water consumption for both pathways in 2050. The hydrogen boilers in the present study are assumed to be condensing boilers, therefore, the efficiency based on higher heating value has been used throughout the study, for the hybrid and hydrogen boiler scenarios.