MSc. Energy Science
Faculty of Geosciences

An end-user cost economic- and environmental comparison of alternative heating scenarios for households in the Netherlands

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Abstract

To contribute to the transition to a carbon-neutral heating system and to the ambition of the Netherlands to reduce their greenhouse gas emissions according to the Paris climate agreement, this research investigated the economic and environmental impact for different alternative heating scenarios seen from the end-user perspective. Even though regional heat transmission models exist to assist the Dutch heat transition, the results are aggregated and not specific enough for the end-user. Existing literature only focuses on either one technology or measure, but an economic and environmental analysis on alternative heating scenarios for the existing buildings seen from the end-user perspective in the Netherlands does not exist. To cover the above gaps, this research developed a new model that investigated the economic and environmental impact of sustainable heating scenarios for a modelling period of 30 years for four housing types for end-users in the Netherlands.

The identification of the most economical and environmental interesting scenario included a three phase method. The first phase of the methodology concerns the development of four scenarios: (I) the reference scenario, (II) the individual all-electric, (III) the Aqua thermal Energy and storage (ATES), and (IV) the Middle Temperature (MT)-heating network scenario. The second phase concerns the model development in which the model is structured and data is incorporated. The third phase contains the analysis of the energy demand and CO_2 emissions, NPV, LCOE, and sensitivity analysis.

This study found that the MT-heating network is for all housing types the most economically and environmentally interesting scenario seen from the end-user perspective because it has the lowest LCOE and the highest NPV after the modelling period. All the alternative heating scenarios require insulation improvements, therefore the energy demand and CO_2 emissions are considerably lower compared to the reference scenario. The MT-heating network is for almost all housing types the most favourable alternative heating scenario in terms of LCOE and NPV. However, for older houses, the natural gas boiler has the lowest LCOE, while for newer houses the MT-heating network turns favourable. Compared to the other alternative heating scenario the MT-heating network has the advantage of relatively low investment, fuel costs, and operational and maintenance costs.

To conclude, this research has shown that different alternative heating scenarios are consisting of a combination of various adjustments, collectively or individually applied. Investment, fuel, and O&M costs vary between the different scenarios and influence the profitability. This model proved to be useful, as it created a methodology that can calculate the energy demand and CO_2 emissions, LCOE, and NPV for different housing types all seen from the end-user perspective under different assumptions for any specific location in the Netherlands. Therefore, this research contributes to the current techno-economic and environmental future assessment of heating technologies at the end-user level in the Netherlands.

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Thank you all. I learned a lot!

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Symbols and abbreviations

Used in formulas	Definition
ρ_{air}	Density of air at 20 degrees Celsius
$O\&M\ factor$	O&M factor given as percentage of the investments
Cp_{air}	Specific heat or air at 20 degrees Celsius
n	Number of connected buildings
A	Specified surface part of a housing type
k	Thermal conductance value
Q	Total collective heat demand
q	Total individual heat demand
CF	Cash flows of year
r	Discount rate

Abbreviations	Definition
ASHP	Air source heat pump
ATES	Aqua thermal energy system
BAG	Basic Registrations of addresses
CapEx	Capital expenditures
CHP	Combined heat and power
COP	Coefficient of performance
ESCOs	Energy service companies
GIS	Geographical information system
GSHP	Ground source heat pump
HDS	Heat delivery system
HDD	Heating degree days
HT	High temperature
HTS	Heat transmissions system
IBHP	Individual booster heat pump
LCOE	Levelized Costs of Energy
LT	Low temperature
MT	Middle temperature
New houses	Housing types built between 1992-2005
NPV	Net present value

O&M	Operation and maintenance
Old houses	Housing types built between 1946-1964
OpEx	Operational expenditures
PV	Photo voltaic
Rc value	Resistance construction value
RD value	Resistance declare value
SEEH	Subsidy scheme for energy savings for your own home (In Dutch: “Subsidie regeling energiebesparing eigen huis”)
TES	Thermal energy storage system
VET	The Energy Transition Act (In Dutch: “De Wet Voortang energietransitie”)

1. Introduction

1.1 Background

Since 2000, the amount of carbon dioxide concentration in the atmosphere has increased ten times more than has occurred in the past 800 thousand years (Lüthi et al., 2008; Bereiter et al., 2015). This increase in CO_2 causes a sharp rise in temperature on Earth (Lüthi et al., 2008; Bereiter et al., 2015). In order to limit a further increase in global temperature, the Paris agreement was signed in December 2015 with the aim to keep global warming limited to 1.5 degrees. The Netherlands have the ambition to reduce their greenhouse gas emissions by 49% in 2030 and 95-100% in 2050 compared to the levels of 1990 (Klimaatakkoord, 2019).

In the Netherlands, roughly 80% of the heating demand is still supplied by natural gas (CBS, 2018). Therefore, a change to a carbon-neutral heating system is of great importance to reach the goals of the Paris agreement. In addition, the outlook for natural gas in the Netherlands changed completely between 2012 and 2018: climate change and the earthquakes in Groningen have led to a change in policy from a financial to an environmental and safety perspective (The Oxford Institute for Energy Studies, 2019). In 2018 the Dutch government announced that production of natural gas from the giant Groningen field will be stopped as quickly as possible and no later than 2030.

Concrete steps that have been taken by the Dutch government regarding natural gas supply are reformulating its policies: since July 2018 new buildings are no more allowed to be connected to the gas grid which is regulated in the law "Wet Voortgang Energietransitie (VET)". However, in the Netherlands, 90% of the existing buildings are connected to the gas grid for which no clear regulation has been set yet (Natuur & Milieu, 2018b). However, the government does have set ambitious plans to remove 200 thousand buildings per year of the grid in the Netherlands by 2030 (Klimaatakkoord, 2019). In order to achieve this, it has been required that every municipality develops a heat transition plan at the municipal level by 2021 at the latest. This will indicates how and when each neighbourhood will be disconnected from the natural gas grid (Klimaatakkoord, 2019). The economic and technical feasibility are other key aspects that will determine the implementation of energy-efficient measures and sustainable heating technologies will take place in each neighbourhood (Amstalden et al., 2007).

The reduction or replacement of natural gas in existing buildings can be lowered by adopting various energy measures, such as energy refurbishment, and can be fully replaced by sustainable heating technologies (Walker et al., 2018; Connolly et al., 2016). Heat pumps are an interesting example of sustainable heating technologies and are designated as a low CO_2 technology that could be implemented at both individual and collective level (Fischer & Madani, 2017). Additionally, collective heating systems such as heating networks could play an important role in the future heat supply. For instance, Hoogervorst (2017) estimated the potential for collective heating in the Netherlands to be 43%.

1.2 Problem definition

The selection of suitable sustainable heating technologies is generally complex and includes several barriers for the end-user or building owner (Soares et al., 2017; He et al., 2019). High investment costs (e.g. insulation and heat pumps) and uncertain payback periods (Bertone et al., 2018; He, et al., 2019) can be a barrier for the end-user[1] who will need to hold the largest share of the upfront costs. Second, the high uncertainty of the development of energy prices and policy measures may also lead to the postponement of measures. A techno-economic analysis helps to identify the investment costs, fuel costs, O&M costs in the short and long term and therefore helps to compare the alternative heating options for different building types in order to overcome these barriers.

Currently, municipalities and end-users need to make decisions based on the analysis available, which mainly focuses on assessing societal costs and emissions. For example, for the specific case for the Netherlands, PBL has formulated five carbon-neutral heat strategies in a recent report called 'start analysis' to study possible pathways to remove the natural gas supply from existing buildings (Wijngaart et al., 2017). This analysis was meant to help municipalities to formulate the heat strategy at neighbourhood level, which needs to be finished by 2021. The five identified strategies were: (I) All-electric, (II) High-medium temperature heating grid, (III) Low-temperature heating grid, and (IV & V) Renewable gas. These heat strategies were incorporated in a techno-economic model the Vesta MAIS model to calculate decarbonisation pathways at neighbourhood level (Wijngaart et al., 2017). The purpose of the Vesta MAIS model is suitable for exploring the heating potential of sources and

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[1] The end-user is defined as the owner of the particular house.

for comparing various strategies on a large spatial scale such as neighbourhoods, municipalities, and provinces. The Vesta MAIS model compares the strategies in terms of costs, energy demand, and CO_2 emissions (Van der Molen et al., 2018). Besides the Vesta MAIS model, other models exist which calculate the costs of sustainable heating options also for neighbourhood and national level, for example, the CEGOIA model and the "Warmte Transitie Atlas". However, the results provided by these models are similar and regarding costs are aggregated and thus, do not give an indication of the impact of the various heat strategies from a specific end-user perspective (Van der Molen et al., 2018; van den Ende, 2018). Although it is planned that end-user costs will be included in the Vesta MAIS model, this has not been done yet, while it has been frequently pointed out to be a main limitation of the current analysis (Van der Molen et al., 2018). Another characteristic of the Vesta MAIS model, is its complexity to be understood and used. Although the model has been made open-source and it comes with elaborated documentation to help municipalities and other relevant stakeholders to perform their own analysis, it has been proved to remain difficult for users not having a certain level of programming skills.

Other studies outside the Dutch context, use other models or methods, and focus either on individual technologies. These studies are not applicable for the Dutch context, as they do not compare the Dutch housing types. Studies have put their effort into looking at the costs of energy retrofits measures, investment decision making, the effect of policy measures and influence of energy prices on a regional level, and comparison between collective and individual alternative heating options.

He (2019) looked into investment decision making optimisation of energy efficiency retrofit measures for multiple buildings in which also a financing budgetary constraint was implemented. He (2019) confirmed the economic profitability of several energy-efficient retrofits for a specific type of building. Although this method could be applied to several buildings and it tackled the high investment upfront costs, it did not focus on Dutch housing types. Energy demand can differ greatly between housing types and thus have a big impact on the economic profitability of energy retrofit measures. Moreover, the scope of this study is not on the economic impact for end-user, but on the effectivity of energy efficiency retrofit measures at the regional level (He, 2019).

Amstalden et al. (2007) investigated the profitability of energy retrofit investments in the Swiss building sector seen from the end-user perspective. According to Amstalden et al. (2007) energy-saving retrofits are highly attractive if energy prices remain high and even more attractive if policy measures are applied. However, this research only focused on the effects of energy prices and policy instruments on energy-saving retrofits and not into decarbonisation technologies. Besides, this research is done for the Swiss building sector and not in the Netherlands. A Dutch study performed by the Netherlands Enterprise Agency (2011) investigated the average insulating costs for different housing types built between 1945 and 2005 in the Netherlands. However, the indicated costs are averages and not applicable to different housing sizes, besides this study also excluded the investigation of different decarbonisation technologies.

Wang (2008) investigated the Levelized Cost of Heat (LCOH) for alternative heating technologies on an individual and collective level in the UK. It compares the LCOH for two types of individual heat pumps and different magnitudes of district heating systems to an individual natural gas boiler. Results show that the LCOH for individual natural gas boilers is significantly lower than heat pumps and district heating. However, this study does not look into a combination of energy retrofit measures and alternative heating technologies seen from the end-user perspective. Besides this study is done in the UK and investigated only a few sustainable heating technologies.

Lund et al. (2018) quantified the costs and benefits of a third and fourth generation district heating system in future sustainable energy systems. According to Lund et al. (2018), the fourth generation district heating system does consist of higher investment and operational costs, whereas the benefits are lower temperature losses, better utilization of low-temperature heat sources, and better efficiencies in the production (Lund et al., 2018). However, the results of this study are nationally calculated for Denmark. Also, this study did not look into a combination of energy retrofit measures and alternative heating technologies at the end-user level for the third generation heating system.

To the best of the author's knowledge, a study that assesses and compares different sustainable heating technologies for different housing types from an economical and environmental angle from the end-user perspective in the Netherlands has not yet been conducted. Moreover, all of the research found above has focused on either individual energy-retrofit measures or collective energy-retrofit measures and either for an individual building or a number of housing types and an integration of these aspects on the end-user level is not yet performed. Moreover, Van der Molen et al. (2018) indicated the need for further research on the neighbourhood and end-user level where more detailed information about specific technical measures and the building level is considered.

To cover the above gaps, this research will first develop a techno-economic model that identifies the economic and environmental impact of sustainable heating scenarios for four housing types in the Netherlands all done from the end-user perspective. The chosen period for the analysis is 30 years, so that the research is aligned with the current Dutch climate goals.

1.3 Research question and aim

This research aims to analyse the economic and environmental impact of sustainable heating scenarios at building level up to 2050 and to create a right methodology that can be applied to all the other Dutch housing types and different technologies than those examined in this study. Furthermore, this research focuses only on heat used for space heating, warm tap water, and electricity usage for the alternative heating technologies and the domestic electricity use for electrical appliances in the building. The main research question of this study has been formulated as:

What is the economic and environmental impact of sustainable heating scenarios for the main existing housing types in the Netherlands up to 2050?

The remainder of this paper is organised as follows. Chapter 2 introduces the theoretical background of this research. In chapter 3, the methodology is explained and further elaborated. Chapter 4 describes the results and the sensitivity analysis. In chapter 5 the discussion is presented. Finally in chapter 6 the conclusion is drawn.

2. Theory

This chapter describes the theoretical background necessary to understand chapter three and four of the research and consists of concepts and definitions used in this research.

2.1 The building typology and energy demand

Currently there are approximately eight million houses in the Netherlands (CBS, 2020a). Information about the Dutch houses can be found in the Basic Registrations of Addresses and Buildings (BAG), a national register of all municipal basic information about addresses and buildings. The BAG is released yearly under the Public Domain license and is an open source. A study performed by the Netherland Enterprise Agency (2011) categorizes the Dutch building stock into seven housing types and four building periods up to 2005 and represents a large part of the existing houses in the Netherlands, this categorization is derived from the BAG structure.

Table 1 Overview of identified houses in the Netherlands, the values given in the table represents share of the Dutch Building stock for houses built between 1946 and 2005 (Netherlands Enterprise Agency, 2011)

	1946-1964	**1965-1974**	**1975-1991**	**1992-2005**
Detached house	6.5%	4%	3.3%	2.6%
Semi-detached house	4.2%	2.1%	3.3%	2.6%
Terraced houses	7.0%	9%	**12.9%***	5.2%
Porch apartments	**3.9%***	1.7%	2.1%	1.0%
Gallery apartments	1.0 %	2.6%	1.6%	1.7 %
Duplex apartments	3.3%	0.3%	1.4%	0.6%
Flat/ other apartments	1.5%	1.8%	1.8%	2.0%

Table 1 shows that terraced houses built between 1975 and 1991 form the largest share of the Dutch building stock for houses (see the bold marking*). For apartments, porch apartments built between 1946-1964 have the largest share. Although the share for terraced houses of the Dutch building stock is lower for the building period 1946-1964 and 1992-2005, these building periods may lead to a better representation of various situations and possible outcomes. As for example buildings from 1992-2005 might have better insulation values and thus require les investment and fuel costs. Besides, these two housing types still form a large share of the total Dutch housing stock. Therefore, this study focuses on these two common housing types:

‘Terraced houses’ and ‘Porch apartments’ with corresponding building periods: ‘1946-1964’ and ‘1992-2005’.

These housing types have various building characteristics: for example, different construction years, types of houses (e.g. detached, apartments) and insulation levels. The combination of these features influences the energy performance of the building and affects its energy consumption. One way to indicate the energy performance of a building is to refer to energy labels which indicate the energy use. Buildings with label A are among the most energy-efficient. The least efficient buildings receive the energy rating G. One way to reduce the energy demand of a house and therefore positively affect the energy label is to apply thermal insulation.

Thermal insulation is a property of materials and structures to minimize the transfer of thermal energy (heat) between two sides of the material structure. If the inside temperature is higher than the outside temperature, energy transport will occur according to the laws of Fourier. A thermal insulator is often expressed in a resistance construction value (Rc-value) and a U-value for windows. The inverse of the Rc-value is the k-value, which is equal to the U-value. A lower k-value ensures a slower transfer of thermal energy (heat) between two sides of the material or construction and thus cause a reduction in required heating demand. Minimum heat losses are key for the implementation of low temperature (LT) technologies (e.g. the electric heat pump), as this technology only functions with LT-heat delivery system (HDS).

An HDS ensures that the heat is released into the rooms and often they are categorised into LT- and HT-HDS. LT-HDS reacts slower than HT-HDS and heating takes longer. LT-HDS are therefore not suitable for poorly insulated buildings. Examples of LT-HDS are floor, wall heating or low temperature radiators (Ovchinnikov et al., 2017). In order to define the minimum level of insulation this study looked at the minimum level of insulation required to function an LT-HDS, which is equal to a minimum Rc-value of 2.5 (TNO & ECN, 2019; Wijngaart et al., 2017).

For space heating no minimum supply temperature is set, while for hot tap water a heating temperature of 60 degrees is necessary to avoid legionella growth (Ovchinnikov et al., 2017). This required temperature is higher than that needed for space heating, and therefore an additional heater is required to provide warm tap water in the building.

For space heating the characteristics of the building (e.g. insulation, orientation) are extremely relevant as the energy in a building is lost via radiation, convection and ventilation (Blok, 2016). The Heating Degree Days (HDD) is a measurement developed to quantify the yearly space heating demand for a building (Janssens et al, 2014) considering varying ambient temperatures. HDD is defined relative to a base temperature and indicates the outside temperature above which no heating is required. The HDD indicates the total number of degrees that is required for the heating system through the complete year to match the base temperature. Often an inside temperature of 21 degrees is desired. An average Dutch household with limited insulation levels gains around 3 degrees Celsius (Blok, 2016). Therefore, a base temperature of 18 degrees is chosen. In addition, various studies show that theoretical heat demand differs from the actual heat demand (Visscher, 2009; Tigchelaar et al., 2013). The theoretical and actual heat demand correspond well with well-insulated buildings with Label A, but the difference increases for poorly insulated housing types (Label F or G). Therefore, a factor for the theoretical and actual consumption is often used in order to calculate the space heating demand (Tigchelaar et al., 2013).

2.2 Potential sustainable heating technologies

Traditionally, thermal energy for heating is supplied by fuel combustion. In the early industrial period until the 1950s, coal was the prevailing fuel for households. After the discovery of natural gas reserves, coal has been replaced. Today in the Netherlands, 90% of the houses uses a natural gas boiler which burns natural gas for the production of space heating and hot tap water (Natuur & Milieu, 2018a; CE Delft, 2019).

A major drawback is that natural gas is partly responsible for the emission of greenhouse gases. However, the fast replacement of coal by natural gas, proves that a transition to sustainable energy sources in relatively short time frame is not unreachable (Verbong et al., 2007). Heat can be generated by alternative heat sources, such as electricity or by direct supply of residual heat. The Start analysis created by PBL identified several alternative heating strategies in which they distinguished between individual and collective strategies. Dutch energy experts often distinguish between individual and collective heating systems as well (Leeuwen et al., 2017; Leguijt & Schepers, 2014).

The Start analysis created five strategies in order to decarbonize the heat supply. The first strategy aims for electrification of the energy demand and refers to the replacement of the natural gas used for heat and warm water supply by electricity-based technologies. There are several individual electric heating options that can replace the natural gas boiler. Alternatives at individual level are: the air-source heat pumps (ASHPs), ground source heat pumps (GSHPs), hybrid heat pumps (in combination with green gas), electric heating, pellet furnaces and solar thermal installations. Heat pumps are electrically driven vapour cycles whereby it is possible to extract heat from the ambient air (low temperature source) and subsequently supply it to the buildings that is to be heated (the heat sink) (Milner et al., 2012). ASHPs often have lower efficiencies in cold winter weeks, which is caused by bigger temperature differences. ASHP generally have a coefficient of performance (COP) for space heating of 3 to 3.5 (CE Delft, 2018a). However, ASPHs do have a lower price and are relatively easy to install in comparison with GSHP (Hakkaki-fard et al., 2015). Other advantages compared to GSHPs are that they require less space and are not ground bounded. In the Netherlands there are already 394 thousand ASHPs installed at individual buildings (CBS, 2017). As GSHPs are ground bounded, more expensive and occupy more space compared to ASHPs, they are less applicable to individual apartments, therefore this study only looked into the ASHPs.

The second strategy created by PBL consists of a collective heating network with middle temperatures (MT) and high temperatures (HT) and includes several variations. Often these heating networks are named third generation heating networks. A third generation heating network, used prefabricated, pre-insulated pipes which are placed into the ground and operates with temperatures below 100 degree Celsius (Lund et al., 2014; Bartnik & Buryn, 2011). For the MT-heating network the supply temperatures are reduced to temperatures of 70 degrees Celsius in order to increase the efficiency of the system. Figure 1 shows a schematic overview of a heating network, and contains: (1) transport piping, (2) distribution heating pipes and (3) connection heating pipes. Distribution pipes are pipes required to distribute the warm water through the neighbourhood. The connection heating pipe is the required pipe from house to the street. Even though piping is also part of the inside of the building, this study assumes that for high rise apartments the existing building pipelines are already available.

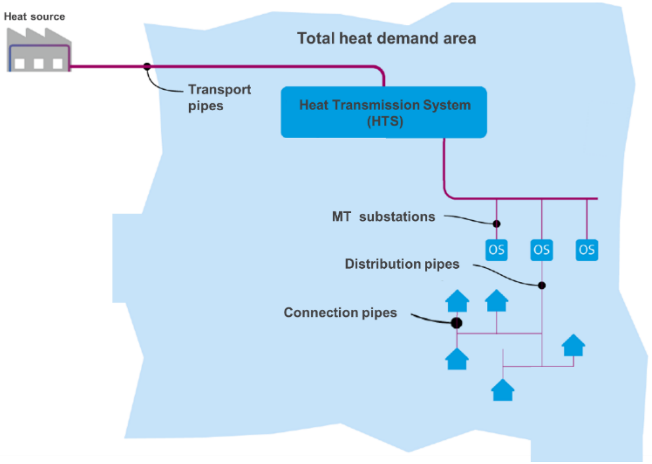

Figure 1 Schematic overview of piping for a MT-heating network

HT- and MT-heating networks usually use natural gas, coal, biomass and residual heat as energy sources and even in some systems solar energy and geothermal are part of the energy mix. Residual heat is considered in urban areas with nearby industrial activity (Rooijers, 2002; CE Delft, 2019). In a CE Delft study on waste heat in the Rijnmond area (such as Rotterdam), residual heat alone has a potential of 1274 MW for heating (Rooijers, 2002). Some of them are built to deliver heat, others produce heat as a by-product which is released into the environment. Emissions for residual heat differ and depend on the type of heat source, fuel used and efficiency. Any heat carrier will dissipate its thermal energy to the ambient temperature until an equilibrium is reached (Fourier's Law). Heat losses depend on several variables, for example, the distance over which the heat is transported and energetic relationships (non-linear heat losses) (CE Delft, 2019). Due to the high energy losses in the HT-heating network, the sustainability of this system can be questioned. Besides, the long term vision of the Netherlands is to move towards medium and low temperature heat sources. Therefore, this study only includes MT-heating networks.

The third strategy consists of a heating network with low operating temperatures and is often referred to as fourth generation heating network. This heating network is engineered to fight climate change and the integration of renewable energy by providing flexibility to the electricity system (Lund et al., 2014). The fourth generation heating network consists of a series of insulated dual pipes that convey a heat carrier from a heat source to the heat transmission system (HTS) and to the end-user (Fremouw, 2012). Although there are technical differences between different heat pipes for different temperature levels, there are no relevant differences in costs (CE Delft, 2019). Some potential heat sources are for example waste from industry (e.g.

datacentres), biomass, solar thermal energy plants, power to heat, shallow and deep geothermal energy and surface water (ECW, 2020). One of the most potential sustainable energy sources in the Netherlands is thermal energy from surface water (in Dutch TEO, in this study ATES). The Dutch government included this source of energy in the climate agreement for roughly 200 PJ (Klimaatakkoord, 2019).

According to Fleuchaus et al. (2018) ATES with a heat pump is particularly applied in the Netherlands. Worldwide roughly 2800 ATES systems are installed of which 85% in the Netherlands (Fleuchaus et al., 2018). ATES system in combination with heating networks are the most used form in which large scale heat pumps are applied (Segers et al., 2019). Surface water is pumped through a heat exchanger and supplies primary heat to a collective heat pump, which subsequently upgrades the water to higher temperatures that can be used for heating or hot tap water. The temperature of the surface water depends on the season and typically varies between 5 and 20 degrees over a year (IF Technology, 2018). This technology is therefore particularly interesting for new construction and thorough renovations in the vicinity of open water surfaces. The main drawback of this system, however, is that the highest heat availability is in summer, while the highest demand is in winter. To tackle this problem usually the thermal energy is stored in a thermal energy storage system (TES) during the summer, in order to supply the stored heat in the winter period (Dahash, 2019). In winter, a collective heat pump extracts heat from the hot spring of the TES and is heated up to 50 or 70 degrees. After usage the water is conveyed back into the cold well. Renewable energy sources in combination with TES are often seen as desired situation in order to balance wind and solar power generation. The electricity surplus caused by the intermittency of wind and solar energy can be used for heat pumps (Lund et al., 2014). Large scale heat pumps are seen as an important technology for smart energy systems in order to achieve high shares of renewable energy in fourth generation heating networks (Lund et al., 2014). One key aspect of designing an LT heating network, is the minimum temperature requirement for hot tap water in order to avoid legionella growth. As legionella can resist temperatures above 50 degrees Celsius. One way to tackle this, is to use an extra Individual Booster Heat Pump (IBHP) per household that provides in the need for hot tap water. As balancing the summer and winter heat demand, tackling the intermittency of wind and solar and reducing the temperature increase by a natural heat source, it was decided to only look into an ATES system in combination with TES system.

The fourth and fifth strategy consists of renewable gas in combination with a hybrid heat pump or a very efficient boiler. New energy carriers which could function as an alternative for natural gas (e.g. hydrogen or green gas) that are also described in the 'Start analyse' (Wijngaart et al., 2017) are not incorporated, because the shift of hydrogen as heating technology in buildings is still a premature option and poses many challenges (Walker et al., 2018).

2.3 Costs of technologies

The implementation and maintenance of individual and collective technology up to and including 2050 entails costs. In this study the total costs of technologies are calculated based on:

- Capital Expenditures (CapEx): CapEx includes all the investment expenditures needed for a scenario in year zero taken into account the investment subsidy as described in Section2.4 and 2.5.
- Operation and maintenance (O&M) costs: yearly O&M costs are given as a percentage of the investment costs.
- Fuel costs: yearly fuel expenditures for a scenario which depends on the amount of fuel and the selected fuel price as described in Section 2.4. The fuel costs consist of the electricity or gas needed for heat supply, electricity for appliances, warm tap water and cooking. In addition, energy generation subsidies are taken into account as described in Section 2.4. and 2.5.
- Reinvestments and lifetimes: when the lifetime of a technology expires within the modelling period, a reinvestment is required.

2.4 Fuel prices development

Fuel costs consist of fixed and variable costs and vary per energy source. In Appendix A: Energy prices and emissions in Table A13 to Table A17 the projected fuel prices for electricity and natural gas are given for 2020, 2030, 2040 and 2050.

- Variable electricity and natural gas costs are formed by the commodity price, energy tax and ODE subsidy. ODE is the tax that is charged on the natural gas and electricity to sustain the sustainability subsidy in the Netherlands (SDE++). Energy tax is regulated by the government and is paid per cubical meter of natural gas and kWh electricity.

- Fixed fuel costs are costs that users pay regardless of their consumption. Fixed fuel costs are a network fee which includes the supply, transport and measuring service for natural gas and electricity

Variable prices for energy carriers are volatile and are determined by global developments. The price expectations for natural gas and electricity are subsequently described according to the Climate and Energy Outlook of 2019 (Schoots et al., 2019):

- Natural gas price: A division in commodity, tax and ODE tax of the natural gas price is necessary, so that the specific announced tax regulation is included in further natural gas price determination. Over the longer term tax on gas is likely to increase up to 2035, although this is still highly uncertain (Schoots et al., 2019). In the short-term there are some concrete plans announced by the government. In 2020, the rate for the first natural gas tax increased by 3.99 cents per cubical meter compared to 2019 (Belastingdienst, 2020). In the six years since 2020, the tax is expected to increase with one cent per cubical meter natural gas per year (Rijksoverheid, 2020a). The expected tax increase on natural gas (Klimaatakkoord, 2019) will lead to more expensive operations costs for natural gas-based technologies, in comparison to electricity based heating technologies. According to Schoots et al. (2019) the global increase in demand and therefore the price for natural gas is mainly caused by the Asian market. In Europe, the energy demand is expected to increase until 2025. After 2030, the energy demand and the price are expected to decrease, thanks to more energy savings and the increasing share of renewable energy in the energy system.
- The Electricity price: The electricity price is expected to remain roughly stable up to 2035 (Schoots et al., 2019), even though it is expected that the electricity production changes greatly. The ban on the use of coal for electricity production will take effect between 2020 and 2030 for the various coal-fired power stations. The Climate and Energy Outlook 2019 assumes a better market position for gas-fired power stations around 2020, which is partly due to the strongly increased CO_2 price. After 2023, the share of natural gas in the electricity supply is expected to decrease again due to the growth of renewable electricity. After all, renewable electricity is cheaper compared to natural gas once the system has been installed as sunlight and wind are free. Besides the development in the Netherlands, electricity prices strongly depend on the development in surrounding countries. As the

electricity price development is highly uncertain it is included Section 3.4 in the sensitivity analysis.

2.5 Subsidies

The Dutch government stimulates a variety of sustainable energy measures and technologies with subsidies. For example, the Dutch government subsidises energy retrofit measures and is regulated in the "Subsidie Scheme for Energy savings for your own home" (in Dutch: 'Subsidieregeling Energiebesparing Eigen Huis' (SEEH)). This regulation includes subsidy for facades, roofs, floors and windows improvements. To be eligible for this subsidy, the requirements of the Dutch government must be met, such as a minimum insulated surface and corresponding minimum resistance declare (RD) and U-values. For facades, roofs and floors a minimum RD value of 3.5 is required and for windows, a minimum U-value of 1.2 (Netherlands Enterprise Agency, 2020). Although the number of layers in the total construction and corresponding RD value ultimately determine the Rc-value, this study assumed that for an Rc-value of 2.5 the required RD-value is met and the minimum surface requirements were omitted. Thus, an Rc-value of 2.5 is eligible for the allocation of subsidy. Besides demand reduction subsidies, there are also subsidies for the generation of sustainable energy categorized per technology and is regulated in SDE++. These subsidies do have different fixed lifetimes, amounts and are technology dependent. In this study the SDE++ subsidies for a collective heat pump (12 year), ATES (15 year) and a heating network (15 year) are incorporated and start in 2021. Besides generation subsidies also investment subsides for sustainable energy exist (ISDE). This study also incorporated this type of subsidy for heat pumps and IBHPs. In Chapter 3, the lifetime and amounts are further elaborated and allocated to the technologies.

3. Methods

This chapter describes the methods necessary to generate the results in chapter four of the research and consists of the research framework, the scenario description, the model development and the analysis. The input data can be found in Appendix B: Techno-economic model input.

3.1 Research framework

The research framework of this thesis is presented in Figure 2. The framework defines three phases and each phase consists of a number of steps and the research question.

(1) The first phase concerns the different alternative heating scenarios.
(2) The second phase concerns the model development and the input data used in the model.
(3) In the third phase the energy demand and emissions, LCOE, NPV (including a sensitivity analysis) of the alternative heating scenarios are carried.

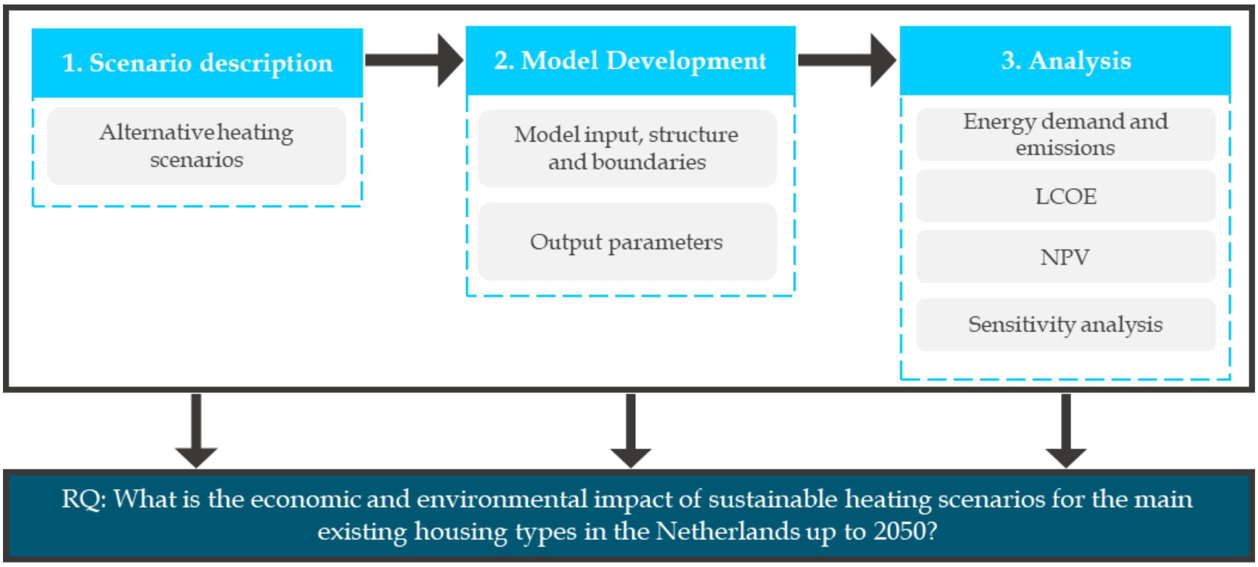

Figure 2 Research framework

3.2 Phase 1: Scenario Description

In this study, all scenarios are based and derived from the strategies of the 'Start analyse' as presented in Section 1.2 and 2.2.

Reference: Natural gas boiler

The reference scenario is established in order to compare it to the calculated alternative scenarios. In this scenario the house is equipped with (1) an individual natural gas boiler and (2) HT-HDS. Both, natural gas and electricity are supplied via the existing grid. Current insulation levels depend on the housing type and corresponding building period.

Scenario 1: Individual all-electric

The measures in this technological scenario are: (1) Current insulation levels are improved to an Rc-value of 2.5 and windows with HR++ glass (2) Individual ASHP; (3) An IBHP; (4) LT-HDS; (5) Removal of natural gas connections in the building and (6) installing the electric cooking requirements (see Figure 3). Note that removing the existing gas infrastructure is not included in this scenario, as it is not part of the research scope.

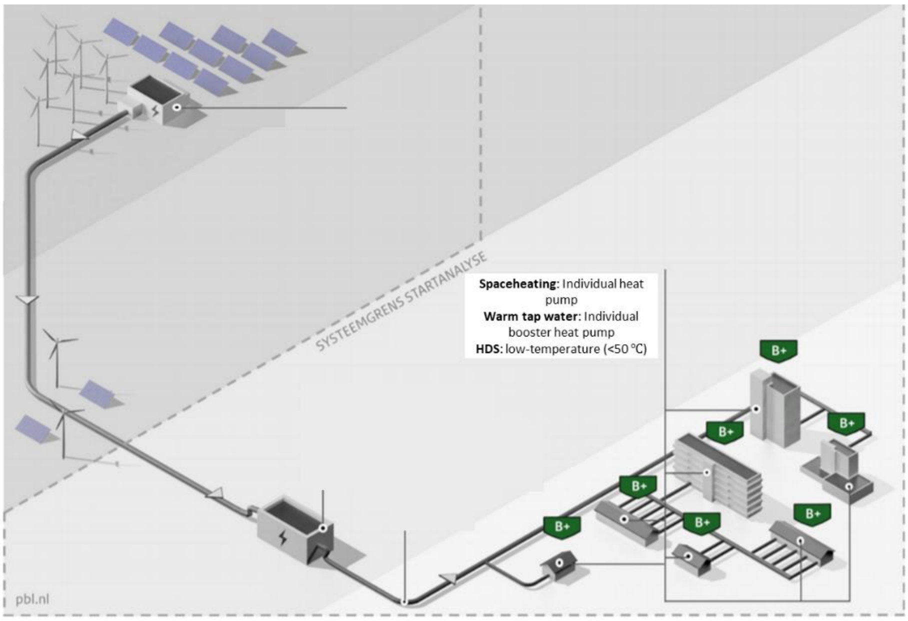

Figure 3 Schematic representation of the individual all-electric scenario (Source: image is partly adapted from: Wijngaart et al., 2017)

Scenario 2: ATES

Applied measures in this technological scenario are: (1) Current insulation levels are improved to an Rc-value of 2.5 and windows with HR++ glass; (2) ATES in combination with a ground source heat pump; (3) IBHP for warm tap water; (4) LT-HDS, (5) Removal of natural gas connections in the building and (6) installing the electric cooking requirements (see Figure 4).

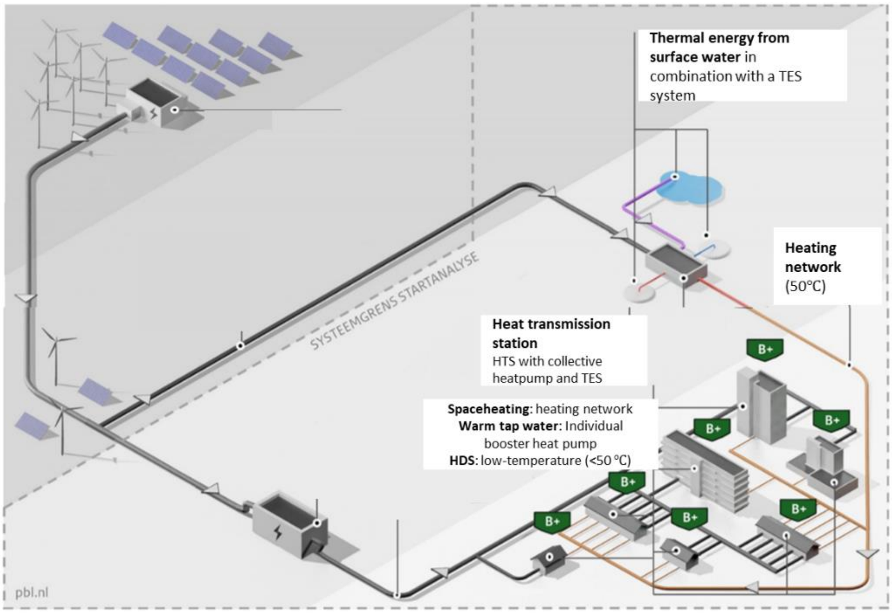

Figure 4 Schematic representation of the collective thermal surface water scenario (Source: image is partly adapted from: Wijngaart et al., 2017)

Scenario 3: Middle-temperature heating network

In this scenario, the buildings are insulated and the heat is directly suitable for space heating and the usage for warm tap water. Also, no further adjustments to the heat delivery system are required. The applied measures in this scenario are: (1) Current insulation levels are improved to an Rc-value of 2.5 and windows with HR++ glass; (2) The MT-heating network is supplied with heat sources with a temperature of 70 degrees Celsius, (3) Removal of natural gas connections in the building and (4) installing the electric cooking requirements (see Figure 5).

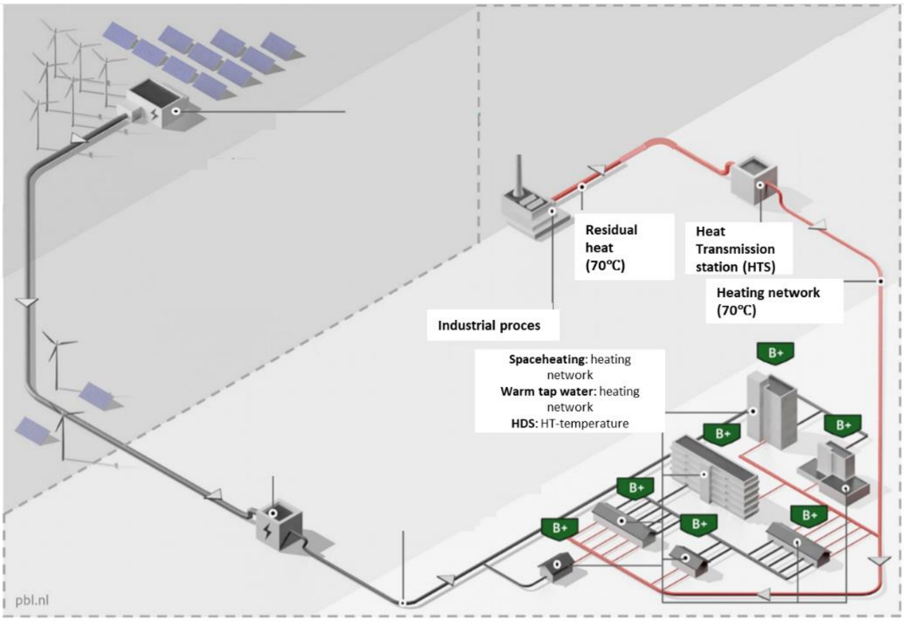

Figure 5 Schematic representation of the MT-heating network scenario (Source: image is partly adapted from: Wijngaart et al., 2017)

3.3 Phase 2: Model Development

3.3.1 Model input, structure and boundaries

The structure of this model is shown in Figure 6 and consists of seven main building blocks: (1) User input, (2) General input data, (3) Building specific input data, (4) Calculation of final energy demand, (5) Cost allocation between individual and collective scope, (6) Technology specific input data and (7) Output parameters.

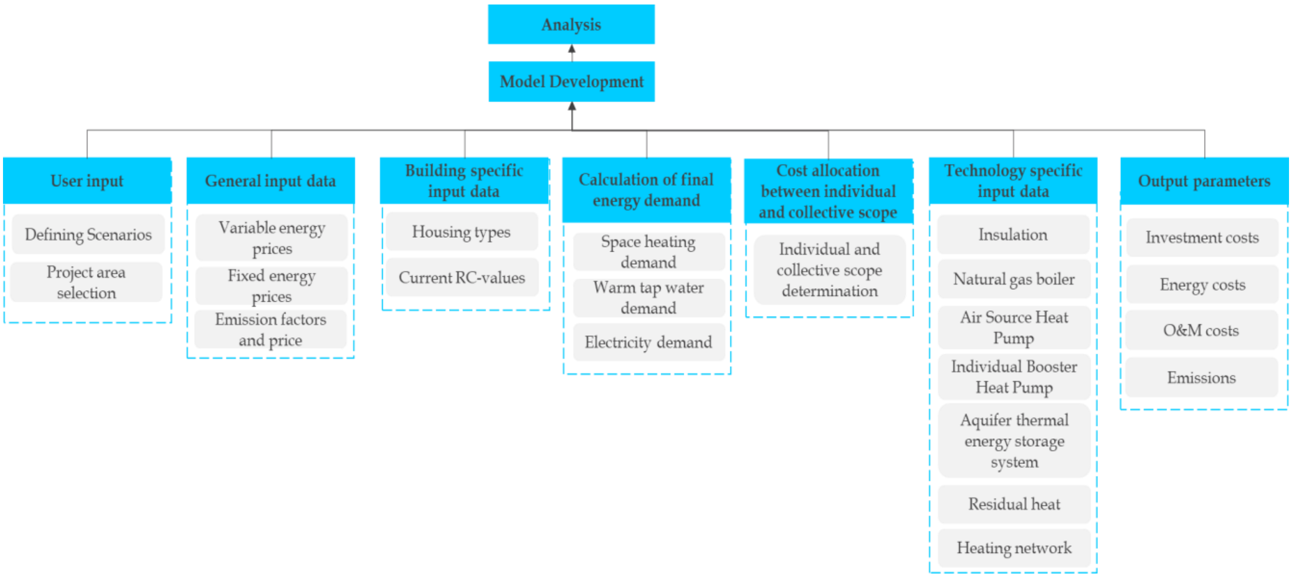

Figure 6 Structure of the model

Note that only the four identified housing types are described in the method and modelled. Furthermore, the model considers the building stock to be constant up to 2050 and does not include demolition and new builds. This study also assumes that all scenarios start operating in the year 2021 with the same projected future lifetimes, taken into account reinvestments. Due to varying energy prices over time the modelling period is set for 30 years. Furthermore, the model assumes that all subsidies start in 2021, whereas no subsidies are applied to reinvestments as prices are assumed to decrease over time. Also, this study assumes that the reinvestment costs are equal to the investment costs of 2020, as this study does not take into account learning curves. Note that the reinvestment costs are first calculated to the present value. Furthermore, the model assumes a constant energy demand per year.

3.3.2 User input

The first building block consists of a user interface, where the user of the model can modify settings (see Figure B29 in Appendix B: Techno-economic model input). The flexibility of the model relies on the possibility to generate different scenarios by simply adjusting or adding some input parameters. To illustrate how the model works, data from a neighbourhood located in the Netherlands named ´Arnhem West´ are taken, but any project area taken from the Netherlands can be plugged into the model. The BAG data for this area is exported to the created model in Microsoft Excel and resulted in a total number of 1.200 houses included the new projected buildings. In the area, there are 58 Porch apartments 1946-1964, 46 Porch apartment 1992-2005, 20 Terraced houses 1946-1964, and 46 Terraced houses 1992-2005. Resulting in a total of 170 buildings. Other parameters that can be adjusted in the model by the user are insulation levels, energy prices, emission factors, discount rates, piping distance, lifetimes, investment costs, and subsidies.

3.3.3 General input data

As introduced in Section 2.3 and 2.4, the relative competitiveness of heat technologies is influenced by the electricity and natural gas price. These are taken as exogenous parameters in the model and are based on historical energy data from 2013-2019 (CBS, 2020b) and the Climate and Energy Outlook for the Netherlands (Schoots et al., 2019). The variable, fixed energy prices and carbon factors are given in Table A13 to Table A17 in Appendix A: Energy prices and emissions.

Variable energy prices

Historical data of the commodity price for natural gas from the period 2013-2019 is taken (CBS, 2019), data from the Vesta MAIS model is used up to 2030 which is based on the Climate and Energy outlook (see Section 2.3). Subsequently, the commodity price is further extrapolated up to 2050 and is aligned with the expected decreasing trend as described in the Climate and Energy Outlook 2019. ODE is assumed to be constant up to 2050, as like is done in the Vesta MAIS model (Wijngaart et al., 2017). The tax on natural gas will increase the first six years by € 0,01 (Belastingdienst, 2020) and are then linearly extrapolated to 2050. A distinction between commercial and private variable electricity prices is made, as prices differ considerably. Existing data from the period 2013-2019 has been taken (CBS, 2019) and data from the Vesta MAIS model is used up to 2030, which is based on the Climate and Energy Outlook 2019 (Schoots et al., 2019). As indicated by the Climate and Energy Outlook (Schoots et al., 2019) and Wijngaart et al. (2017) the electricity price is expected to be stable (see Section 2.3), therefore a stable electricity price is assumed after 2030.

Fixed energy prices

In the Netherlands, electricity and natural gas are subdivided between large and small consumers, for which different fixed prices apply (Liander, 2020a). Historical data from the years 2015 to 2020 of fixed natural gas and electricity prices (Liander, 2020b) is extrapolated to 2050.

Carbon factors and price

CO_2 emission factors for electricity and natural gas are used in the model. For electricity, it is assumed that the supplied electricity is generated with the same energy source. Currently, electricity in the Netherlands is largely supplied to the end-user by coal and natural gas, therefore the average electricity emission factor is used (Lijst emissiefactoren, 2020). This study also assumes that the emission factors, as used in 2020, remain the same and that there will be no shift from one energy carrier to another[2]. For residual heat no emissions are taken into account (ECW, 2020).

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[2] The emission factors towards 2050 are changing due to national and European policies (Wielders et al., 2017). However, this is not included in the calculations.

3.3.4 *Building specific input data*

The building-specific input data used consists of the current insulation levels (Netherlands Enterprise Agency, 2011) and are given for the different housing types and periods (Table 2).

Table 2 Current insulation levels for different housing types (Netherlands Enterprise Agency, 2011).

Building period	**Rc-value Floor**	**Rc-value Flat roof**	**Rc-value Inclined roof**	**Rc-value Closed wall**	**U-value single glass**	**U-value double glass**	**U-value HR++ glass**
Unit	$\mathrm{m}^2 \cdot \mathrm{K} / \mathrm{W}$	$\mathrm{m}^2 \cdot \mathrm{K/W}$	$\mathrm{m}^2 \cdot \mathrm{K/W}$	$\mathrm{m}^2 \cdot \mathrm{K/W}$	$W/m^2 \cdot k$	$W/m^2 \cdot k$	$W/m^2 \cdot k$
1946 – 1964	0.32	[-]	0.39	0.36	5.2	2.9	1.8
1992 – 2005	2.53	2.53	[-]	2.53	5.2	2.9	1.8

3.3.5 *The calculation of the final energy demand*

In order to calculate the relevance final energy demand of a building the energy required for space heating, warm tap water and electricity are considered. In Appendix B: Techno-economic model input the required data to calculate the final energy demand is given.

Space heating demand

In Equation 1 the radiation and convection losses (q) in GJ are calculated with the k_i value, A_i and HDD of the building (PBL, 2018; Janssens, et al., 2014) and in Table 3 the variables are defined. The k_i value for each surface of the building is calculated by the Rc-value $\frac{1}{Rc_i}$.

$$q_{i,radiation\ and\ convection} = k_i \cdot HDD \cdot A_i \qquad [GJ] \qquad [1]$$

Table 3 Variables used to calculate the final energy demand

Variable	**Unit**	**Unit of measure**	**Definition**
A_i	-	m^2	Specified surface part of a housing type
k_i	-	$W/m^2 \cdot k$	Thermal conductance value
HDD	2500	-	Heating degree days
N	1.26	m^3/h	Ventilation rate
V	-	m^3	Volume
ρ_{air}	1.05	kg/m^3	Density of air at 20 degrees Celsius
Cp_{air}	1.006	$kJ/kg.K$	Specific heat
n		-	Number of connected houses
t		years	Year
i		-	Individual housing type
T		years	Projected lifetime

Due to different characteristics of the building types, the surface of the building parts are often not similar. Therefore, a ratio per building part per housing type is calculated. This ratio is determined by dividing the amount of square meters of the facade by the total floor area. Hence, this enables to allocate heat loss per individual housing type. Ventilation losses are calculated with Equation 2. The ventilation losses depends on the specific heat of air, the ventilation rate, the volume of warm air that is lost, the density of air and the amount of square meters. Furthermore, a floor height of 2.5 meters is assumed.

$$q_{i,ventilation} = N \cdot V \cdot \rho_{air} \cdot Cp_{air} \cdot A_i \cdot (T_{out} - T_{in}) \qquad [GJ] \qquad [2]$$

The radiation, convection and ventilation losses for each façade are summed, and results in the energy demand for space heating per housing type ($q_{i,t}$) (see Equation 3). Subsequently, the space heating demand has been multiplied with the actual and theoretical factor as is described in Section 2.1.

$$q_{i,t} = (q_{ventilation,i,t} + q_{radiation\ and\ convection,i,t}) \cdot factorSH \qquad [GJ] \qquad [3]$$

Where:

$$i = \{1, \ldots, n\}$$

$$t = \{0, \ldots, T\}$$

The collective heat demand is the sum of heat demand respectively of all individual houses considered (see equation 4). Where n is defined as the number of connected houses.

$$Q_{i,t} = \sum_{i=1}^{n} q_{i,t} \qquad [GJ] \qquad [4]$$

Warm tap water demand

A fixed value has been chosen for warm tap water per housing type (Schepers et al., 2019), which is given in Table B19 in Appendix B: Techno-economic model input.

Electricity demand

Domestic electricity consumption depends on the type of house, the number of appliances and the number of family members (Milieucentraal, 2020). Electricity consumption data per housing type for two family members and corresponding building year are retrieved from Milieucentraal (2020). The assumed values are given in Table B20 in Appendix B: Techno-economic model input.

3.3.6 Cost allocation between individual and collective scope

This section explains the cost allocation between individual and collective heat generation (see Figure 7).

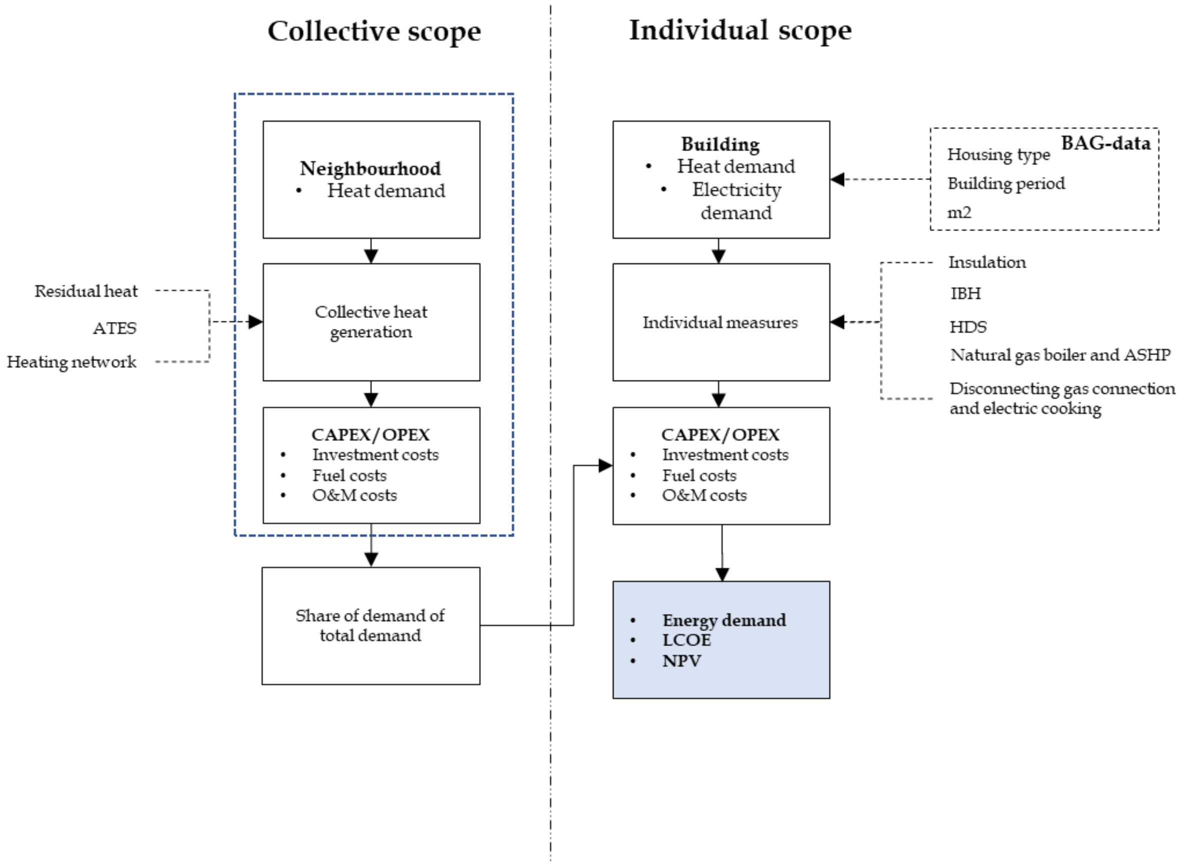

Figure 7 Cost allocation between individual and collective scope of alternative heating scenarios

The figure shows a difference between the individual and collective scope. The individual scope consist of measures that occurs within the building. Collective individual measures are blocks within the dotted line and form the collective energy generation. Finally, the light grey block contains part of the analysis explained in Phase 3. Collective energy generation technology costs are area dependent and are supply heat to more than only one building. To allocate the costs of collective scenarios to the end-user at the individual level, a fraction is created. This fraction is the individual heat demand proportional to the total heat demand. Furthermore, several assumptions are made: (I) Each end-user is capable of financing their investment costs; (II) The capacity of the LT and HT radiators is sufficient to heat the house and (III) All buildings are independently connected to the current energy networks.

3.3.7 Technology specific input data

This subsection describes the researched technical options. A difference between building measure, individual and collective technologies is made. All costs are exclusive VAT.

Building measure - Insulation

Economic parameters for insulation are provided by existing studies (Netherlands Enterprise Agency, 2011). Insulation prices are from 2011 and an inflation rate of 2% has been applied to calculate these to present values (see Table 4).

Table 4 Techno-economic parameters for insulation (The researched insulation prices by Netherlands Enterprise Agency are calculated with an inflation rate of 2% per year to the present.)

	Unit	**Floor**	**Flat roof**	**Incline roof**	**Facade**	**HR++ glass**	**Reference**
Investment insulation	€/m^2	20	193	53	21	281	Netherlands Enterprise Agency, 2011
SEEH subsidy	€/m^2	-7.00	-20.00	-20.00	-6.00	-35.00	Netherlands Enterprise Agency, 2020
Lifetime	Years	50	50	50	50	50	Loos van der, 2016
Rc/U-value	m^2 K/W or W/m.K	2.5	2.5	2.5	2.5	1.2	Nieman, 2016

Furthermore, the size of the investment costs for insulation depends on the surface in square meters per building part (Ai) and the price of insulation per square meter (see Equation 5). Costs are only allocated if the building part does not meet the Rc-value of 2.5.

$$Investment\ costs\ insulation_i = \sum_{i=1}^{n} Inv.insulation_A \cdot surface_{A,i} \qquad [euro] \qquad [5]$$

Building measure - Heat delivery system in the building

Two types of heat delivery systems were investigated, low temperature (LT)- and high temperature (HT) radiators. Techno-economic parameters are provided by existing studies (Schepers et al., 2019;) and are shown in Table 5. Equation 6 and 7 show how the investment costs for LT and HT radiators are calculated.

$$Investment\ costs\ HDS_{HT} = HT\ radiators\ price\ per\ m^2 \cdot floor\ surface \qquad [euro] \qquad [6]$$

$$Investment\ costs\ HDS_{LT} = LT\ radiators\ price\ per\ m^2 \cdot floor\ surface \qquad [euro] \qquad [7]$$

Table 5 Techno-economic parameters used for the Heat distribution systems

Type of HDS	Investment costs		O&M	Lifetime	Reference
	House	Apartment	Percentage of investment	Years	
LT radiators	€ 14 per m²	€ 18 per m²	3%	30	Schepers et al., 2019
HT radiators	€ 8 per m²	€ 8 per m²	3%	30	Schepers et al., 2019; CE Delft, 2018a; CE Delft, 2018b)

*Building measure - D*isconnecting natural gas connection and electric cooking
Disconnecting the natural gas connection and implementing electric cooking involve costs (see equation 8 and Equation 9). The average removal costs of the three largest network operators (Stedin, 2020; Liander, 2020b; Enexis, 2020) are used and are shown in Table 6.

$$Investment\ costs\ disconnecting\ Gas\ connections = number\ of\ houses \cdot Gas\ disconnecting\ costs \qquad [euro] \qquad [8]$$

$$Investment\ costs\ eletric\ cooking = number\ of\ houses \cdot Electric\ cooking\ costs \qquad [euro] \qquad [9]$$

Table 6 Techno-economic parameters for the disconnect the natural gas supply and electric cooking

Type	Investment costs	Reference
Permanently disconnect the natural gas supply	€ 547	(Stedin, 2020; Liander, 2020b; Enexis, 2020)
Electric cooking	€ 1,200	(Natuur & Milieu, 2020c)

Individual - Natural gas boiler

Techno-economic parameters for the natural gas boiler are provided by existing studies (Schepers et al., 2019; CE Delft, 2018a). The investment costs for heat generation consist of the purchase and installation of a natural gas boiler. All techno-economic parameters technologies are given in Table 7.

Individual - Air Source Heat pump

As the model needs to cope with the differences in heat demand of different housing types, the capacity of an ASHP depends on the heat demand (see Equation 10). The required capacity for an ASHP is calculated with an average amount of 1.640 full load hours per year and represents the full load hours for an average household in the Netherlands (Niessink, 2019; CBS & RVO, 2015). All techno-economic parameters technologies are given in Table 7.

$$Capacity\ ind.ASHP = \frac{Heat\ demand\ (q_{i,t}\ )}{full\ load\ hours\ ind.HP} \qquad [kW] \qquad [10]$$

In order to cope with this varying capacity, a distinction is made between fixed and variable investment costs (Schepers et al., 2019). Although, the subsidy for an ASHP is capacity dependent and can easily be found in the subsidy list provided by the government (Netherlands Enterprise Agency, 2020), this study assumed one fixed amount of subsidy of € 1,900 (Schepers et al., 2019) for the studied buildings, because of the huge diversity in subsidies.

Individual - Booster heat pump

An additional IBHP is in some situations required in order to supply warm tap water. Even though, also for an IBHP the subsidy varies, this study assumed a fixed subsidy of € 650 (Netherlands Enterprise Agency, 2020). All techno-economic parameters technologies are given in Table 7.

Table 7 Techno-economic parameters Individual all-electric scenario

Type	**Investment costs**	**O&M costs**	**COP/efficiency**	**Lifetime**	**Subsidy**	**Reference**
Natural gas boiler	€ 2,000	2%	90%	15 years	€ 0	Schepers et al., 2019
Individual ASHP	€ 4,998 and € 410 per kW	2%	3.50	15 years	€ 1,900	Schepers et al., 2019
IBHP incl. buffer tank	€ 3.500	2%	2.20	15 years	€ 650	Netherlands Enterprise Agency, 2020; Schepers et al., 2019

Collective - Low temperature system: Aqua thermal energy storage

Like an individual ASHP, the required capacity of the ATES system with TES is also demand dependent. Therefore, the capacity is derived from the total heat demand dividing by the total amount of equivalent full load hours of the system multiplied by the simultaneity factor (SF), which is the sum of the maximum demand of the various part of a system to the coincident maximum demand of the whole system (Equation 11). Generally, a SF applies to 40 buildings or more, at fewer buildings the simultaneity is greater and rising to 1.0 (Schepers et al., 2019). An SF_{LT} of 0.55 is used (Schepers et al., 2019). The equivalent full load hours are taken from the required heating demand as researched by IF Technology Creating Energy (2018). This study assumed no minimum and maximum capacity for this technology due to the complexity of the system.

$$Total\ req.power\ LT = \sum_{i=1}^{k} \frac{Total\ demand\ (kWh)}{full\ load\ hours} \cdot SF_{LT} \qquad [kW] \qquad [11]$$

The investment costs consisting of the HTS, collective heat pump, and ATES system are capacity dependent and are calculated with Equation 12.

$$\begin{aligned} &Investment\ costs\ ATES \\ &\quad = Total\ req.power_{LT} \\ &\quad \cdot (Var\ HTS + Var\ Coll.HP + Var\ HTS + ATES_{var}) \\ &\quad + Fixed\ coll.HP + Fixed\ ATES + Fixed\ TES \end{aligned} \qquad [euro] \qquad [12]$$

The required energy for (heat) pumps are considered as fuel costs and do take into account 20% transport losses of the total heating network. The efficiency of the collective heat pump is represented by a COP value of 4 (Schepers et al., 2019). The insertion in summer and extraction in winter of the TES requires energy for pumping. This study does not look into the supply of cold water for cooling. The different energy requirements from insertion and extraction occur because of a larger temperature difference in the heat exchanger when extracted, while this leads to a smaller temperature difference for insertion. This leads to less cubical meters that need to be transferred resulting in a lower GJe/Gj heat (Netherland Enterprise Agency, 2019). Furthermore, since 2020 subsidies are allocated to this technology (Lensink, 2020). The SDE ++ 2020 for ATES includes a basic amount of € 0.115 per kWh for a term of 15 years and for a collective heat pump € 0.038 per kWh for 12 years (Lensink, 2020). In Table 8 the techno-economic parameters are given.

Table 8 Techno-economic parameters for the ATES system

Type	Investment costs	O&M costs[3]	COP/Efficiency	Lifetime	Subsidy	Reference
ATES[4]	€ 90,000 and € 103.5 per kW	3% and 0%	40	30 years	€ 0.115 per kWh for 15 years	Schepers et al., 2019
TES[5]	€ 135,000 and € 198 per kW	2% and 0%	0.0025 GJ_e/GJ_{cold} and 0.018 GJ_e/GJ_{hot}	30 years		Schepers et al. 2019; Netherland d Enterprise Agency, 2019
HP collective	€ 547,50	3.5% and 2.5%	4	15 years	€ 0.038 per kWh for 12 years	Schepers et al., 2019
HTS[6]	€ 113.85 per kW	3% and 3%	0.0072 GJ_e/GJ_{th}	30 years	€ 0.038 per kWh	Schepers et al., 2019

Collective - Medium temperature system: Residual heat

In the model configuration, this study assumes that the HTS is able to handle peak demands, has enough capacity in order to meet the given heat demand, and that no extra combustion unit should be present. The MT-HTS system costs are given in Equation 13. This implies that the costs are underestimated as the back-up boilers generally need to cover 18% of the heat demand, however, this highly depends on the system characteristics (Segers et al., 2019). A pump distribution ratio of 0.0072 GJ_e/GJ_{th} to distribute heat is assumed (Netherlands Enterprise Agency, 2019). Techno-economic parameters are given in Table 9.

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[3] First value is for operational costs second is for service costs applied in the same manner in the rest of the study.

[4] ATES includes costs of the pump system, heat exchanger and piping cost for transport pipe with a length of maximum 5 km (Schepers et al., 2019).

[5] TES includes costs for the two wells and heat exchanger (Schepers et al., 2019).

[6] HTS cost includes costs for a heat transfer station with heat exchangers to feed into the network (Schepers et al., 2019).

$$MT - HTS\ system = Var.costs\ HTS \cdot Total\ required\ power_{MT} \qquad [euro] \qquad [13]$$

Table 9 Techno-economic parameters middle temperature heating network

Type	Investment costs	O&M costs[3]	Efficiency	Lifetime	Reference
Var costs HTS	€ 135 per kW	3% and 3%	0.0072 GJ_e/GJ_{th}	30 years	Schepers et al., 2019; Netherlands Enterprise Agency, 2019

Collective - Heating network - Transport piping

Heating network investment costs are formed by the costs needed for transport, distribution, and connection pipes. Transport piping costs depend on the required diameter and length of the pipe in order to sufficiently supply the heat demand (see Equation 14, which is adapted from Schepers et al., 2019). The transport piping distance from the source to the distribution network for the MT-heating network is set to a thousand meters. This is derived from two big residual sites in the Netherlands (TATA steel and Shell Pernis). However, note that this distance is highly location-dependent and therefore is changeable in the model settings. Subsequently, the investment costs for transport pipes are calculated (see Equation 15).

$$Cost\ pipe = 805 \cdot (Total\ req.power)^{0.55} \qquad [\frac{euro}{m}] \qquad [14]$$

$$\begin{aligned} &Investment\ costs\ MT\ transport\ piping \\ &\qquad = Cost\ pipe\ per\ meter \cdot distance \end{aligned} \qquad [euro] \qquad [15]$$

CE Delft has created a calculation method for ATES and TES systems, which is derived from a realized project called: "De Teuge" in Zuthphen. In the project area, 187 ground-level buildings mute within an ellipse with an area of 15,762 m^2. The costs per square meter for the distribution system is derived, which is multiplied by the project area (see Equation 16 adapted from Schepers et al., 2009).

$$\begin{aligned} &Investment\ costs\ Distr.heating\ pipes\ LT\ ATES \\ &\qquad = (6000 \cdot \frac{187}{15741}) \cdot Area \end{aligned} \qquad [euro] \qquad [16]$$

For MT distribution pipes Equation 14 is used. First, the total required capacity of the selected area is calculated according to equation 17. This study assumes a connection capacity per building of 7 kW for an MT-heating network and 6 kW for the LT heating network (Scheper et al., 2019). In addition, an SF_{MT} of 0.1 is used.

$$\begin{aligned} &Total\ required\ power_{MT} \\ &\quad = \sum_{i=0}^{n} Connection\ capacity\ \cdot SF_{MT}\ \cdot (1 + transport\ loss) \end{aligned} \qquad [euro] \qquad [17]$$

The total required power MT is then used in order to calculate the price per meter according to Equation 14 and subsequently applied in Equation 18 with a factor MT of 1.59099 adapted from Scheper et al.. (2019). This factor identifies the relationship between the surface of a demand area and the pipe length required. The area is set equal to the total usable floor area of all buildings selected by the model.

$$\begin{aligned} &Investment\ costs\ Distr.heating\ pipes\ MT \\ &\quad = Cost\ pipe \cdot Factor\ MT\ \cdot \sqrt{area} \end{aligned} \qquad [euro] \qquad [18]$$

Collective - Heating network - Connection heating pipes

Equations 19 and 20 are adapted from the study performed by Schepers et al. (2019) used for the determination of the cost per meter for LT and MT pipes and are used in Equation 21. Furthermore, this study assumes that the connection piping distance is 5 meters, measured from the house to the street, confirmatory data was not found for this parameter. Techno-economic parameters are given in Table 10.

$$Cost\ pipe = \ 610 \cdot (Capacity\ house_{LT})^{0.5} \qquad [\frac{euro}{m}] \qquad [19]$$

$$Cost\ pipe = \ 610 \cdot (Capacity\ house_{MT})^{0.5} \qquad [\frac{euro}{m}] \qquad [20]$$

$$\begin{aligned} &Investment\ costs\ connection\ pipes \\ &\quad = average\ HS\ distance\ \cdot Costs\ pipe \cdot number\ of\ houses \end{aligned} \qquad [euro] \qquad [21]$$

Table 10 Techno-economic parameters for the heating network

Type	**Investment costs**	**O&M costs**[3]	**Efficiency (losses)**	**Lifetime**	**Subsidy**	**Reference**
Heating network	Pipe diameter dependent	3% and 3%	20%	30 years	€ 0.053 per kWh	Schepers et al., 2019; Lensink, 2020)

3.3.8 Output parameters

The output of the model consists of the (re)investment costs, O&M costs, fuel costs, and emissions (see Table 11). The equations used to calculate the O&M costs and fuel costs are given in Appendix C: Output used.

Table 11 Overview of the different cost components for the scenarios

Scenario	**End-user costs components**			
	Investment costs	**Fuel costs**	**O&M costs**	**Emissions**
Reference scenario	• Natural gas boiler • HT-HDS	• Natural gas and electricity	• Natural gas boiler • HT-HDS	• Emissions for electricity and natural gas
Individual all-electric scenario	• ASHP • Insulation • LT-HDS • IBHP • Natural gas removal and electric cooking	• Electricity	• ASHP • LT-HDS • IBHP	• Emissions for electricity
ATES scenario	• ATES • TES • Collective HP • LT- Heating network • Natural gas removal and electric cooking • Insulation • IBHP • LT-HDS	• Electricity for pumps	• ATES • TES • Collective HP • LT- Heating network • LT-HDS • IBHP	• Emissions for electricity
Middle temperature heating network scenario	• HTS • MT- Heating network • Insulation • HT-HDS • Natural gas removal and electric cooking	• Electricity for pumps	• HTS • MT- Heating network • HT-HDS	• Emissions for electricity and heat

3.4 Phase 3: Analysis

This phase consists of the analysis of the described output parameters in Phase two in order to determine the energy demand and emissions, the LCOE, NPV, and a further description of the sensitivity analysis.

3.4.1 Energy demand and emissions

The heat demand is identified per housing type before and after insulation. Also, the energy usage and CO_2 emissions of technologies are investigated.

3.4.2 LCOE

Techno-economic assessments are important to advice decision making by quantifying and assessing different alternative heating options, and understand how to mitigate carbon emissions in a cost-effective manner (Wang, 2018). The Levelized Costs of Energy (LCOE) is an appropriate method in modelling and comparing the costs for different alternative technologies (in euro per produced unit of energy) (Varro et al., 2015) (see Equation 22). In order to calculate the LCOE, the sum of all future cash flows (CF) over the modelling period (t) for the end-user consisting of the (re)investment costs, O&M, and Fuel costs are discounted to the present by using the discount rate (r). Taken into account subsidies in year zero. As to the discount rate, Wijngaart et al. (2019) recommend a discount rate of 6% for end-users. MWh represents the amount of energy produced in the year t.

$$LCOE = \frac{\sum \frac{Investment_t + O\&M_t + Fuel\ costs_t}{(1+r)^t}}{\sum \frac{MWh_t}{(1+r)^t}} \qquad [\frac{euro}{MWh}] \qquad [22]$$

3.4.3 NPV and discounted payback period

The NPV calculates the present value of expected future cash flows using a discount rate in order to be able to compare current and future expenditures under given technical and economic assumptions (Varro et al., 2015). The NPV looks at the profitability of a scenario and is useful to determine the economic attractiveness from the end-user perspective. The LCOE and NPV are closely interrelated (see Equation 23). Besides the NPV, also the discounted payback period (DPBP) is calculated in order to determine the economic profitability of a scenario. It identifies the number of years it takes to break even from the initial investment.

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} - initial\ investment \qquad [euro] \qquad [23]$$

3.4.4 Sensitivity analysis

As in this research, several assumptions are made regarding the input data, it is of great importance to understand the impact of the assumptions on the output values. The criteria to select the input parameters are either a high uncertainty or a strong effect on the output. The results of the sensitivity analysis show the effect of a change in input parameters and show the robustness of the most economic and environmental scenarios. The analysed sensitivity parameters in this research are varying the electricity price, discount rate and the heat demand. In addition, there is also explained why a change in natural gas price and building costs are not included in the sensitivity analysis.

Natural gas price

Similar to the high uncertainty of the electricity price, the natural gas price is also highly uncertain. However, because the modelling approach of this model in which all scenarios are compared to the reference scenario, varying the natural gas price will affect the outcome but no mutual differences between the alternative scenarios will occur. Therefore, the impact of a lower and higher natural gas price is not included in the sensitivity analysis.

Insulation costs

Insulation improvement costs are taken from an existing study performed by (Netherlands Enterprise Agency, 2011). The identified costs are average costs and are categorized per housing type. Average values may lead to higher or lower costs for a specific building when the process is complicated by unforeseen circumstances (for example limited space for the application of insulation). Instead, costs could also be lower as the total street would take insulation at the same moment and therefore become eligible for collective lower prizes. Even though these costs are highly uncertain, the constructed scenarios all include the same insulation costs and therefore would not have affected the scenario preference, but only the two housing types. Therefore, it was decided not to investigate the effect of lower and higher insulation costs.

Improved insulation values

The Dutch government tries to encourage people to invest in sustainable measures at a natural moment[7]. In the standard modelling procedure, this study assumed that the end-user did not make any insulation improvements, and thus current insulation values as researched by the Netherlands Enterprise Agency (2011) were used. However, many households insulated their houses in the period between 1986-2018, especially in roof, wall, and floor insulation (Rijksoverheid, 2020b). Subsequently, this leads to a change in heat demand and affects the economic and environmental performance of the scenarios. On the contrary, it might occur that a building has even lower insulation levels as expected, as average values were used as described in the section before "Insulation costs". Other studies identified the effect on heat demand by changing the heat demand by 50% (Wang, 2018). This study examines the effect of an increased (30%) and decreased (30%) heat demand.

Discount rate

The discount rate has a large influence on future costs as it discounts future costs to the present. The chosen discount rate depends on the type of investor and end-user (Leguijt et al., 2017), for societal investments a discount rate of 4% is often used (Schepers et al., 2019). For private investors and end-users, even higher discount rates of 10 or 12% are used (Outlook, 2015). In this study, the effect on the NPV and LCOE is investigated after changing the discount rate from 4%, 6% (normal), and 12%.

Electricity price

As described in Section 2.4 Fuel prices development prices of energy carriers are volatile and are determined by global developments (Schoots et al., 2019). The future development of the electricity price is highly uncertain, and the development of recent years also shows that prices can vary widely (Schoots et al., 2019). For example, in 2018 the minimum price for the baseload on the APX exchange market was 38.8 euros per megawatt-hour and the maximum price was 63.3 euros (60% increase). Therefore, the first part of the sensitivity analysis investigates the effect of a 30% higher and 30% lower electricity price.

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[7] This is the time of replacement where the existing material is at the end of its lifetime.

4. Results

This chapter describes the results derived from the methodology as presented in 3.4 of this research.

4.1 Energy demand and emissions

Figure 8 and Figure 9 show the final energy demand for the two investigated housing types. The largest reduction happens for older houses (built between 1946-1964), while a relatively small heat reduction is achieved after insulating the relatively newer houses (built between 1992-2005). For example, a terraced house built between 1946-1964 has a heat demand (89 GJ), which is roughly three times more than a terraced house built between 1992-2005 (29 GJ). Very poor insulation levels of old buildings, where the Rc-levels are almost equal to zero, leads to these large differences. Almost 80% of the used energy for old houses is required for space heating in the reference scenario, whereas 40% is used for newer houses.

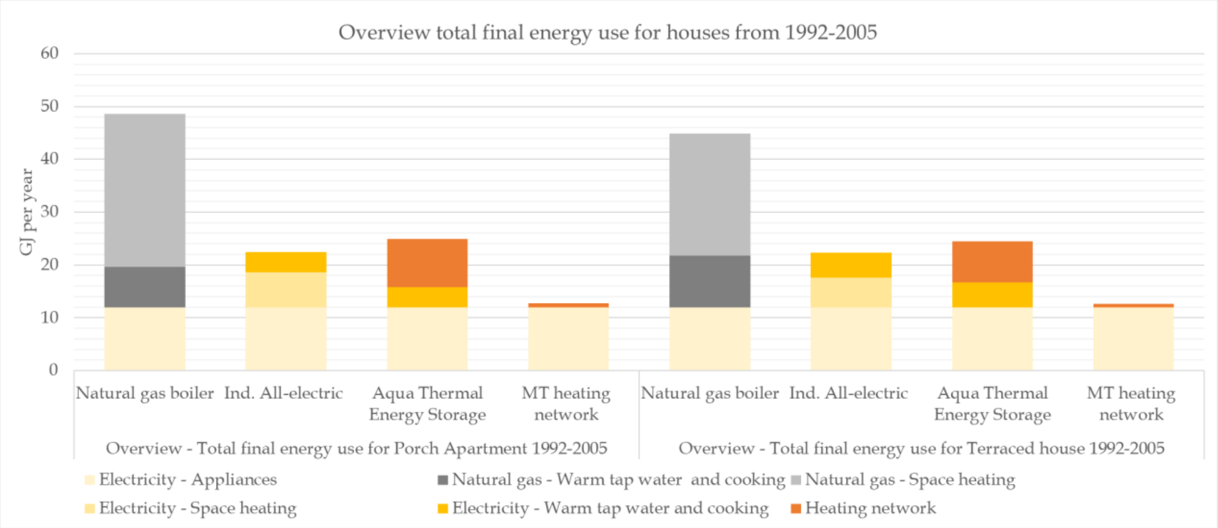


Figure 8 Final energy demand for the scenarios for houses built between 1992-2005 for 2050

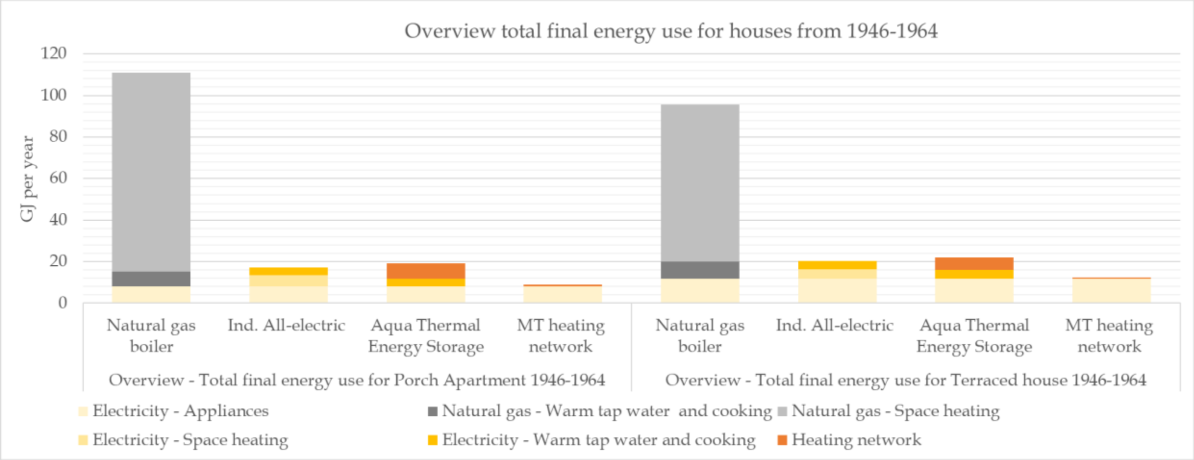


Figure 9 Final energy demand for the scenarios for houses built between 1946-1964 for 2050

A comparison in terms of energy input for the generation of heat seen from the end-user perspective leads to different results. For example, in the individual all-electric scenario, electricity is required to function the heat pump which consumes almost 7 GJ per year, while the ATES scenario consumes almost 10 GJ per year. This difference is caused by the electricity required for pumps part of the heating network, in order to function the TES, ATES, and the collective heat pump. The collective heat pump is responsible for almost 80% of the electricity input. The MT-heating network uses the lowest energy for heat generation, as it only uses electricity for distribution pumps necessary for the distribution of warm tap water and heat for space heating. Note that, the MT-heating network uses a source of residual heat, which does not require any further heating, as this study assumed that the heat is residual heat, whereas in comparison to the individual all-electric and ATES scenario the greatest electricity consumption is done by the collective heat pump.

Warm tap water is in the individual all-electric and ATES scenario generated by an IBHP, which leads to a higher electricity demand of 720 kWh per year. However, 60% of the final energy is saved compared to the reference scenario due to the higher efficiency of the IBHP. In the MT-heating network scenario, the warm tap water is directly supplied by the heating network, as supply temperatures are high enough to meet the legionella standards. Finally, the replacement of cooking on natural gas leads to an increase in electric cooking in all scenarios in electricity consumption of 342 kWh per year.

Figure 8 shows a more detailed overview of the demand reduction per building part after insulation for the housing types. The biggest energy reduction for old apartments is achieved after insulating the floor (80%), flat roof (75%) and facades (70%), compared to the reference situation. For old terraced houses, the largest heat demand reduction is noticed in floor and incline roof (80%), and the facades (70%). Relatively small heat demand reduction is achieved by the replacement of glass, whereas the energy reduction in the building period 1992-2005 only happens in the replacement of double glass by HR++ glass (38%), as façade, roof, and floor insulation do already match the Rc-value of 2.5.

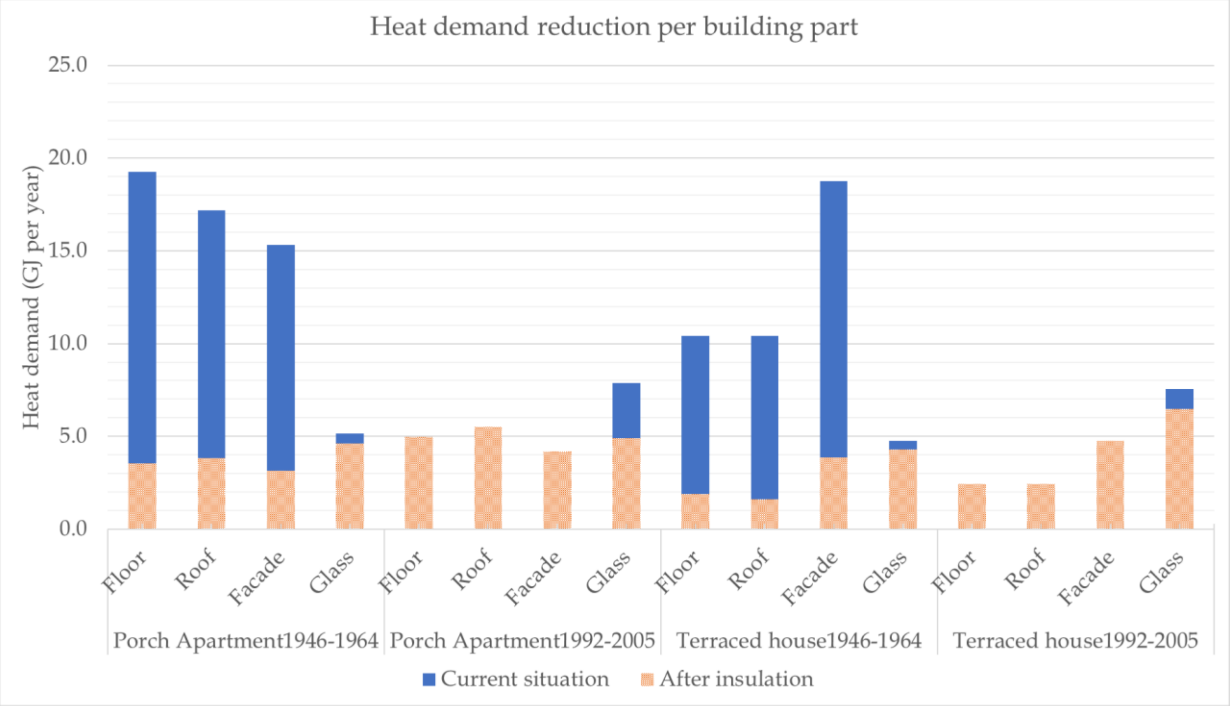


Figure 8 The heat demand per building part before and after insulation for the different scenarios and housing types

Emissions

Figure 10 and Figure 11 show that the CO_2 emissions for electricity, natural gas, and heating network differs per housing type. First, domestic electricity consumption takes up a large share, varying between 50% to 80%, of the total measured CO_2 emissions, while roughly 10% of the emissions are allocated to warm tap water and the remaining part to heat production. The reference scenario for old houses has the highest CO_2 emissions (7000 kg CO_2 emissions per year), due to the relatively larger and fossil-fuel-based heat demand. The ATES scenario emits 3000 kg CO_2 emissions per year, which is more than half of the reference scenario. Emissions for heating are mainly caused by the high energy demand for pumps. The individual all-electric scenario does perform better in terms of CO_2 emissions compared to the ATES and emits around 300 kg CO_2 less per year. However, the differences are small and are mainly due to higher electricity consumption for pumps in the heating network. Where the ATES and individual all-electric scenarios require a large part of electricity to heat water by means of the heat pump, this does not apply to the MT-heating network scenario. As this scenario gets its heat from residual heat for which a CO_2 emission factor of zero is assumed. Comparing the scenarios for newer buildings, one can notice that the reference scenario almost emits even levels of CO_2 emissions in comparison to the ATES scenario, as the reference scenario for newer buildings has much better insulation levels and therefore a lower heating demand. Despite the fact that the total CO_2 emissions are reduced, at least compared to the reference scenario, the electrically driven scenarios offer the possibility of obtaining the required electricity in a sustainable way, which makes these scenarios future-oriented. Another point of attention is the used emission factor for electricity. In the current analysis, the electrically driven scenarios are negatively affected by the constant emission factor (see Section 3.3.3). However, a decreasing emission factor for electricity production which is caused by the increasing share of more sustainable energy in the system (Wijngaart et al., 2017), would positively affect these scenarios more in comparison to the reference scenario, as the emission factor for electricity is expected to decrease.

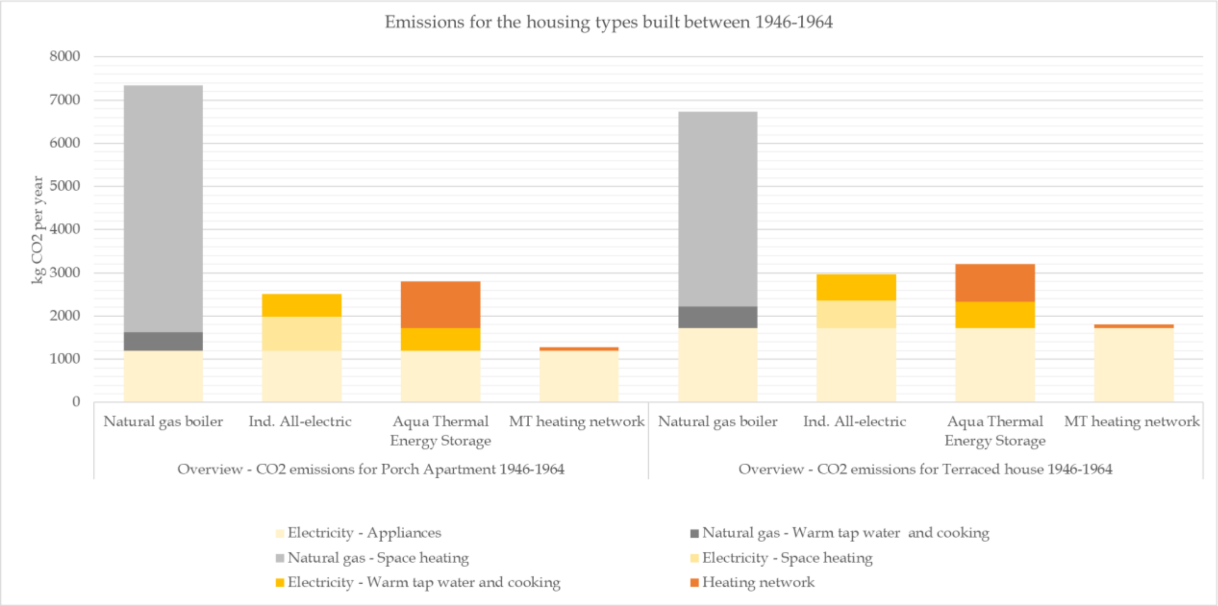


Figure 10 CO_2 emissions for the scenarios and for the two housing types built between 1946-1964.

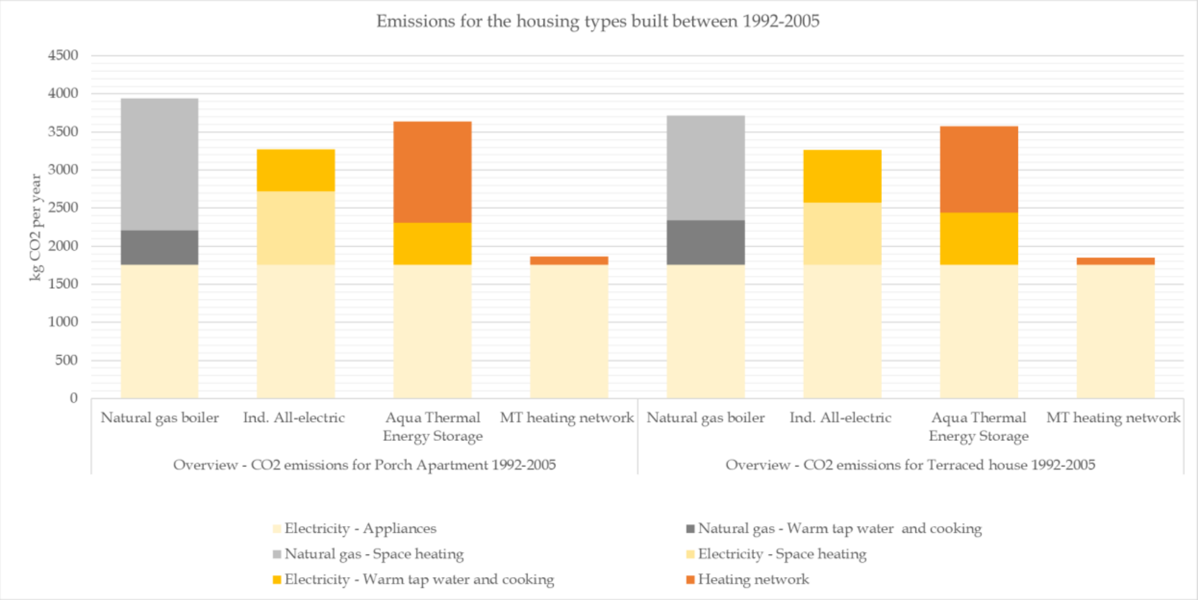


Figure 11 CO_2 emissions for the scenarios and for the two housing types built between 1992-2005.

4.2 LCOE and total investment costs

Figure 12 shows the results of the total LCOE for the four different scenarios and housing types. Overall, the LCOE is lower for houses with a high annual heat demand (see Figure 8 and Figure 9). Also, the difference between the reference scenario and the alternative heating scenarios becomes larger when the heat demand decreases in the four identified housing types. In this study, the LCOE for apartments is lower compared to the terraced houses, due to the larger energy consumption. As expected, the reference scenario has the lowest LCOE for both old housing types and varies between € 130 to € 175 per MWh due to the relatively low investment costs and higher heat demand (see Figure 13 and Figure 14). The individual all-electric scenario is clearly the most expensive alternative heating scenario in terms of LCOE for all types of houses, which nearly reach the € 300 per MWh. The LCOE for the individual all-electric scenario for older houses is more and less 55% more expensive compared to the reference scenario. Meanwhile, the ATES scenario is 45%, and the MT-heating network 20% more expensive than the reference scenario. However, following the methodology, not all costs are incorporated in the scenario analysis, in particular for the collective ATES and MT-heating network scenarios. Important aspects that are currently missing in the analysis are the costs required to remove the old gas heating network and the strengthening of the electricity grid. Implementing these two aspects will lead to higher investment costs, and therefore affects the LCOE.

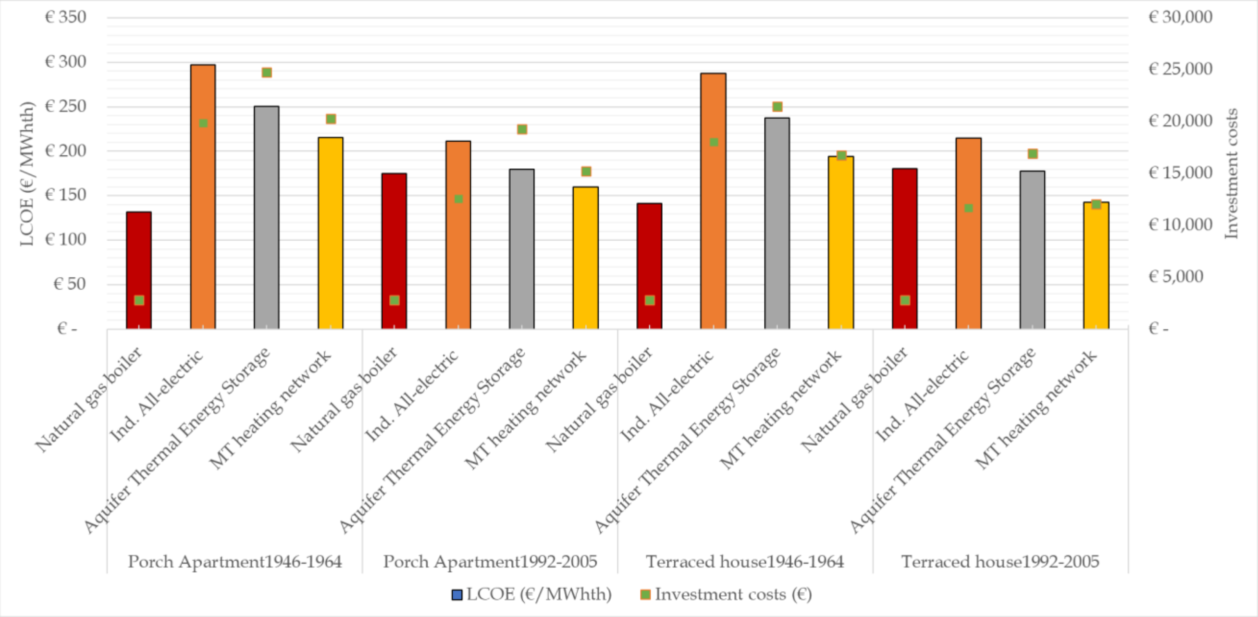


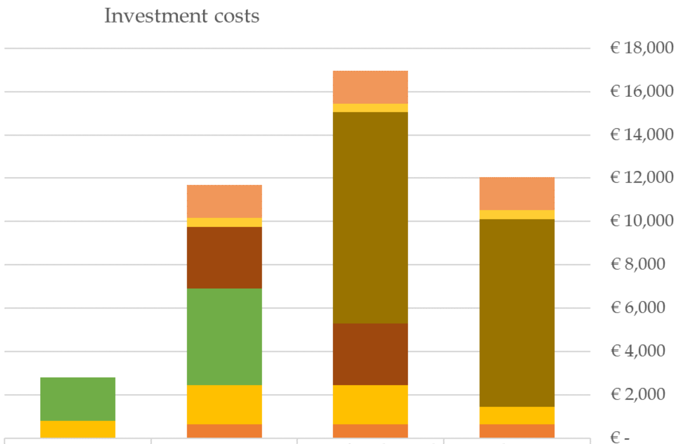
Figure 12 LCOE for different scenarios and housing type.

For new houses, the differences between LCOE are relatively smaller compared to the older houses. Despite the lower energy demand of the reference scenario, the LCOE for the individual all-electric scenario and ATES scenario for porch apartments are still higher compared to the reference scenario, whilst the MT-heating network scenario has a 15% lower LCOE.

Figure 12 also compares the investment costs for the four different housing types and scenarios. The figure shows that the ATES scenario has the highest investment costs for all housing types varying between € 17,000 and € 22,500. The MT-heating network scenario is the second expensive scenario and costs vary between € 12,000 up to € 18,000. The individual all-electric scenario has the lowest costs of the alternative heating scenarios, but are very close to the MT-heating network scenario. Investment costs for this scenario vary between € 11,000 up to € 17,500. The reference scenario has the lowest investment costs of almost € 3,000. Although the investment costs of the individual all-electric are lower compared to the ATES and MT-heating network scenario, the LCOE is still higher.

Figure 13 and Figure 14 are used in order to compare the differences in costs in more detail for terraced houses. First, buildings built between 1992-2005 require fewer investment costs (€ 657) for insulation, before it meets the given insulation standards, while this reaches € 7,350 when the building starts with a lower insulation level, as is the case for older buildings.

Comparing the different energy generation technologies, one can notice that the collective heat production takes a large share of the total investment costs for the ATES and MT-heating network scenario. The collective heat generation contains the generation technologies as they are indicated in Section 3.2 in Table 8. The individual heat production contains the natural gas boiler in the reference scenario and the ASHP in the individual all-electric scenario. In particular, the ASHP in the individual all-electric scenario is around 45% cheaper compared to the collective heat production in the ATES scenario and 40% cheaper than the collective heat production in the MT-heating network system. However, note that the ATES system and individual all-electric scenario both require an additional IBHP for warm tap water, whereas the MT-heating network and reference scenario do not. Furthermore, there is a small difference noticed in the individual heat production costs between old and new houses, this is caused by a difference in heat demand resulting in bigger capacity for the ASHP for newer houses and thus higher costs.



	Natural gas boiler	Ind. All-electric	Aquifer Thermal Energy Storage	MT heating network
🟧 Electric cooking	€ -	€ 1,500	€ 1,500	€ 1,500
🟨 Gas connection removal in building	€ -	€ 413	€ 413	€ 413
🟫 Coll Heat production	€ -	€ -	€ 9,733	€ 8,668
🟫 IBHP		€ 2,850	€ 2,850	€ -
🟩 Individual Heat production	€ 2,000	€ 4,458	€ -	€ -
🟨 Heat distribution system	€ 800	€ 1,800	€ 1,800	€ 800
🟧 Insulation	€ -	€ 657	€ 657	€ 657

Figure 13 Investment costs for a terraced house 1992-2005 for the different scenarios

	Natural gas boiler	Ind. All-electric	Aquifer Thermal Energy Storage	MT heating network
🟧 Electric cooking	€ -	€ 1,500	€ 1,500	€ 1,500
🟨 Gas connection removal in building	€ -	€ 413	€ 413	€ 413
🟫 Coll Heat production	€ -	€ -	€ 7,548	€ 6,723
🟥 IBHP		€ 2,850	€ 2,850	€ -
🟩 Individual Heat production	€ 2,000	€ 4,152	€ -	€ -
🟨 Heat distribution system	€ 800	€ 1,800	€ 1,800	€ 800
🟧 Insulation	€ -	€ 7,350	€ 7,350	€ 7,350

Figure 14 Investment costs for a terraced house 1946-1964 for the different scenarios

Figure 15 illustrates the total cost compositions of the LCOE for the different scenarios and housing types, including investment costs, fuel costs, and O&M costs for the total modelling period. For the reference scenario, the investment costs contribute to less than 10% of the overall LCOE and fuel more than 90%, while this reversed in the alternative scenarios. The ATES scenario has for all housing types the highest share of investment costs varying between 45% and 60%. In addition, this scenario has a smaller share of fuel costs (10% to 30%). Although earlier was described that the required energy for heating was higher compared to the other alternative scenarios, the fuel costs are considerably reduced by the relatively high energy generation subsidy for the ATES. This subsidy only applies for 15 years and after these years the fuel costs for this scenario rise again. Even though the MT-heating network has the second-highest O&M costs in terms of euros, it forms the largest share of the total LCOE (22% to 32%), followed by the ATES scenario (21% to 31%). The share of O&M costs for the individual all-electric scenario is relatively lower compared to the other scenarios (roughly 10%).

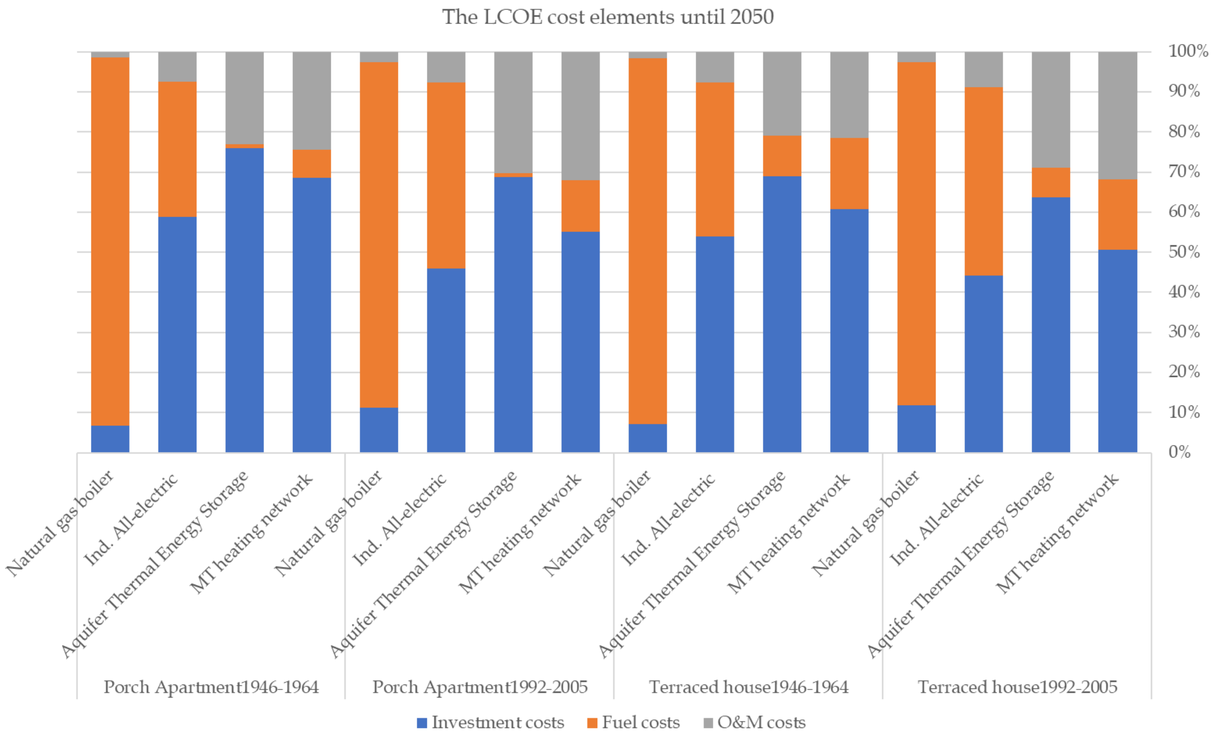


Figure 15 The LCOE elements for the different scenarios and housing types

4.3 NPV

With respect to the NPV, Figure 16 depicts the energy savings, (re)investment costs, fuel costs, and O&M costs for the two housing types and both building periods for all scenarios compared to the reference scenario for the given modelling period.

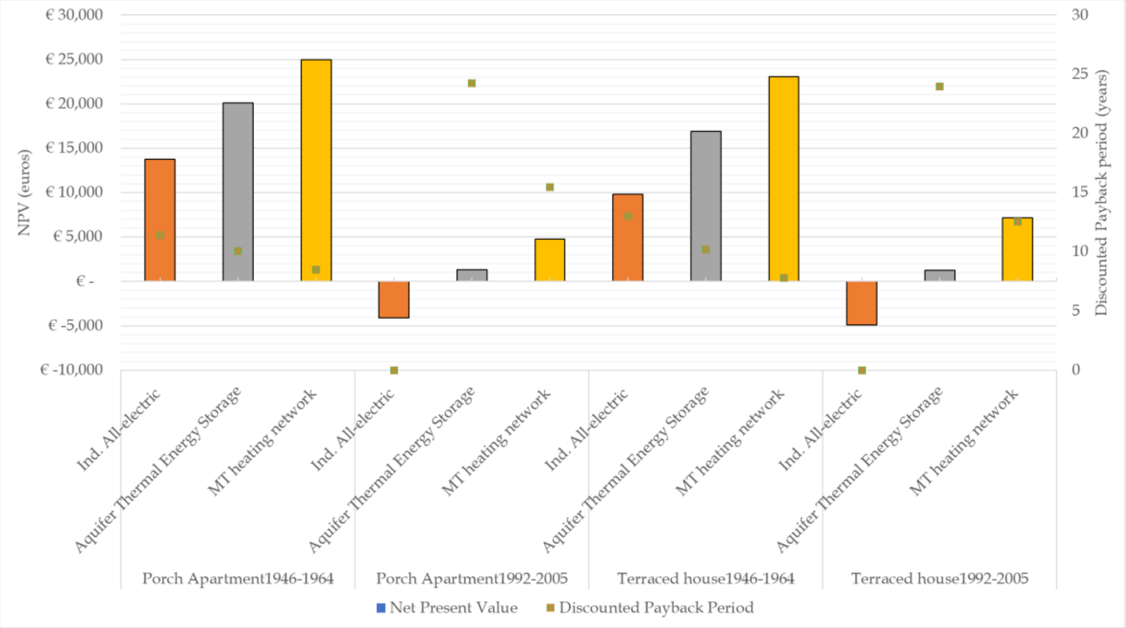


Figure 16 Net Present Value and Discounted Payback Period for different scenarios and housing types

Figure 16 shows that for older housing types all NPVs turn positive. The MT-heating network scenario has the highest NPV at the end of the modelling period (the year 2050), followed by the ATES scenario, which is almost 20% lower compared to the MT-heating network scenario, and almost 55% lower to the individual all-electric scenario. The profitability of the scenarios is mainly influenced by the high fuel costs in the reference scenario for older buildings, which results in greater fuel savings in the long-term compared to the newer houses. Section 4.1 identified that the heat demand for apartments is higher compared to that for terraced houses, this is also why the NPV for the scenarios for apartments is higher than the ones for Terraced houses.

Results look different for newer housing types, where a much smaller reduction in fuel costs is achieved, and investments are relatively high compared to the reference. For newer housing types, the total fuel costs of the reference scenario are much lower compared to the old housing types. Therefore, the NPV for the individual all-electric scenario is not turning positive at the end of the modelling period, except for the MT-heating network and ATES scenario. Overall, the MT-heating network scenario is for most housing types the most economically attractive for the end-user, as it results in the highest NPV. The balance between investment, energy and O&M costs makes this scenario over time more attractive, whereas this combination is less for the ATES scenario. Meanwhile, the relatively higher fuel costs for the individual all-electric scenario makes this scenario less attractive.

Figure 16 also shows the DPBP for the different scenarios and housing types. The MT-heating network scenario has overall for all housing types the lowest DPBP and varies between 8 to a maximum of 15 years. Second is the ATES scenario, with a DPBP varying between 10 years for old buildings and 24 years for newer buildings. The individual all-electric scenario is the least financially attractive scenario in terms of DBPB, as for old housing types the DBPB varies between 11 to 13 years, while for newer housing types the scenario is not refundable. Overall, the DPBP is much higher for newer housing types, than for newer older housing types.

4.4 Sensitivity analysis

Following the methodology, the sensitivity analysis measures the impact of changing input parameters on the LCOE and NPV and is threefold. The effect of changing the discount rate, electricity price, and heat demand is investigated.

4.4.1 Varying the Discount rate

Figure 17 and Figure 18 show both that all NPVs are decreasing by a higher discount rate, which fits as to the discount rate the NPV is inversely proportional to the discount rate, thus a higher discount rate causes a lower NPV. Scenarios that are most affected are the ATES and MT-heating network scenarios, as they become economically less favourable as the discount rate increases compared to the individual all-electric scenario and are caused by higher operational costs in these scenarios. For example, the NPV of the MT-heating network for porch apartments 1946-1964 (green line) decreases from almost € 35,000 to € 5,000. The ATES scenario (light blue line in Figure 17) even hits a negative NPV value by a maximum discount rate, while scenarios with lower operational costs as the individual all-electric (yellow line in Figure 17) are less affected by a change in the discount rate.

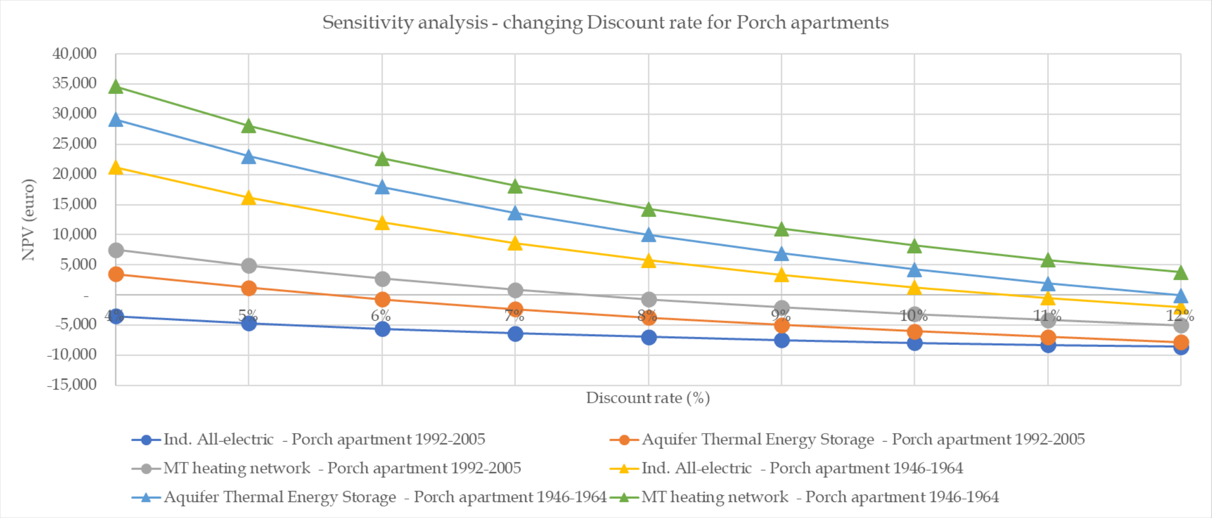


Figure 17 Sensitivity analysis – The effect on the NPV by changing the discount rate for Porch apartments

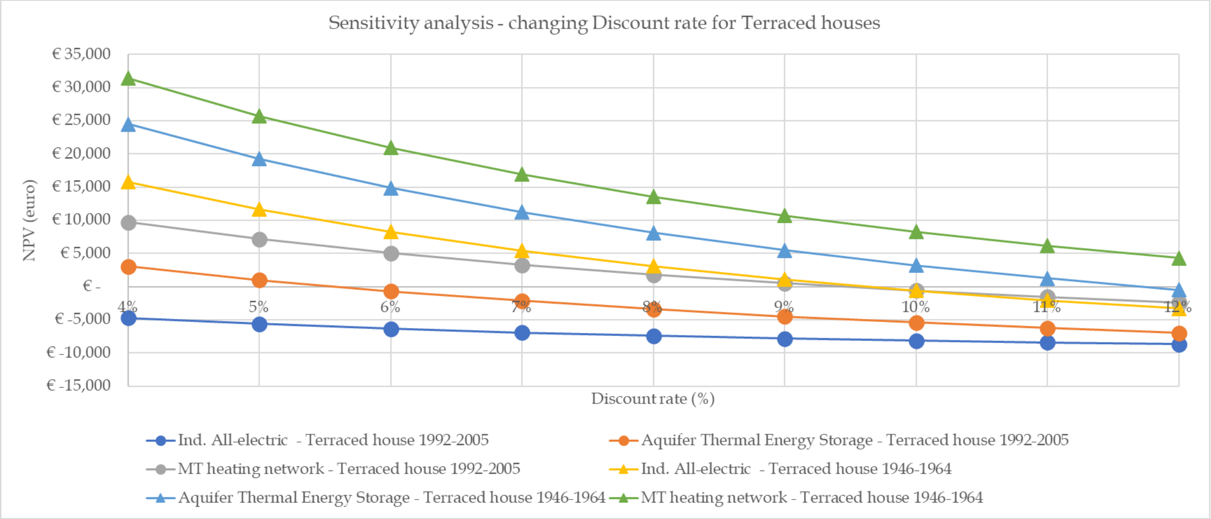


Figure 18 Sensitivity analysis – The effect on the NPV by changing the discount rate for Terraced houses

Figure 19 and Figure 20 show that an increase in discount rate leads to higher LCOE in all alternative heating scenarios. Scenarios with relatively high investment costs and future cash flows (e.g. ATES scenario) are affected more adversely than scenarios with relatively low investment costs and future cash flows (Individual all-electric scenario). Results show that the reference is less influenced by a change in the discount rate because the investment costs are much lower compared to the other scenarios (see Figure 13 and Figure 14). In general, the alternative heating scenarios are highly affected by a change in the discount rate, as scenarios increase with almost 25 to 40%.

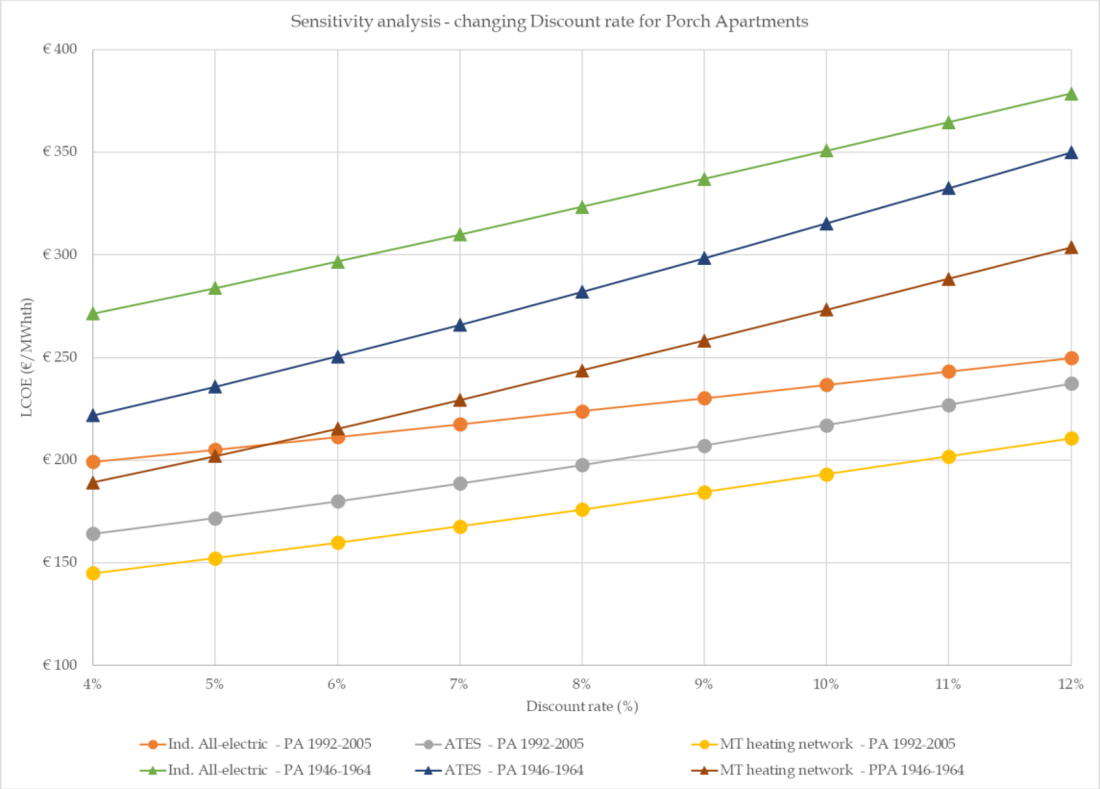


Figure 19 Sensitivity analysis – The effect on the LCOE by changing the discount rate for porch apartments

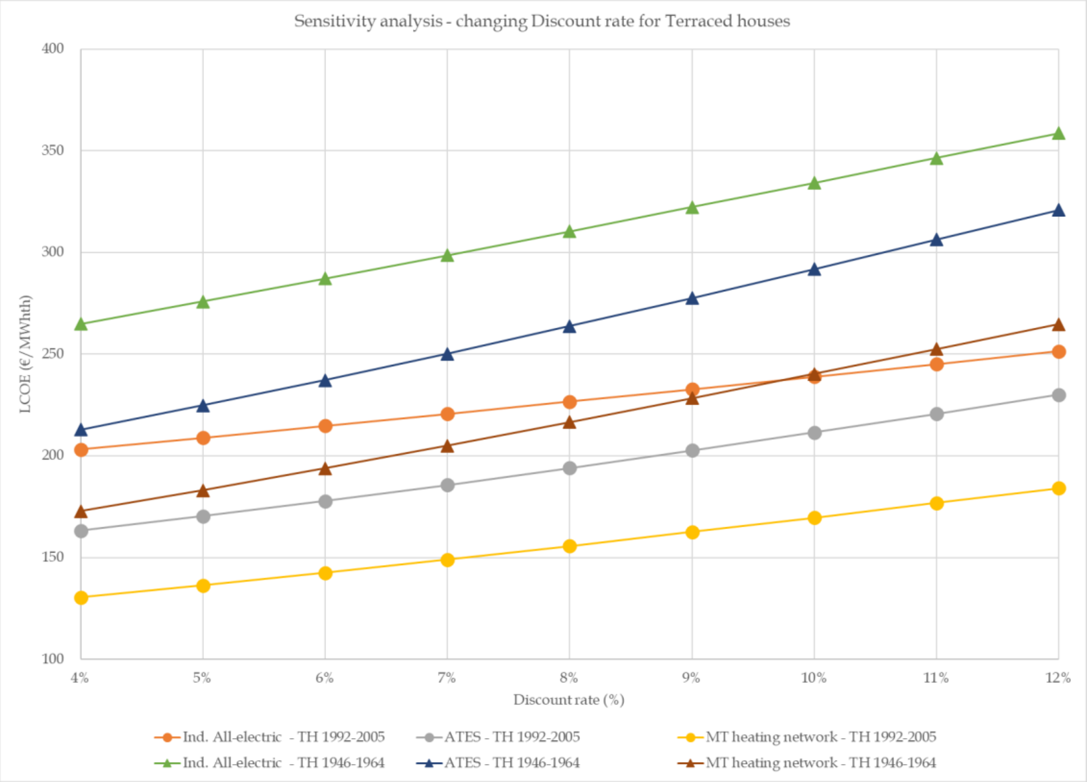


Figure 20 Sensitivity analysis – The effect on the LCOE by changing the discount rate for terraced houses

4.4.2 Varying the electricity price

When varying the electricity price, one can notice that the NPV for the individual all-electric and ATES scenarios are decreasing by a higher electricity price, whereas the MT-heating network scenario remains almost equal and therefore favourable (Figure 21 and Figure 22). The individual all-electric scenario is most affected by a change in electricity price. For example, for a terraced house built between 1946-1964 (yellow line in Figure 17), the NPV decreases with almost 25% if the electricity price increases, while the MT-heating network (green line in Figure 17) decreases slightly with 4%. This difference is caused by the relatively lower electricity consumption of the MT-heating network compared to individual all-electric and ATES scenarios. In addition, the individual all-electric scenario is even more affected than the ATES scenario, as a consumer electricity price was used, while for the ATES scenario commercial prices are used, which are lower. Figure 22 shows this, as the individual all-electric is more affected (22%) compared to the ATES scenario (12%).

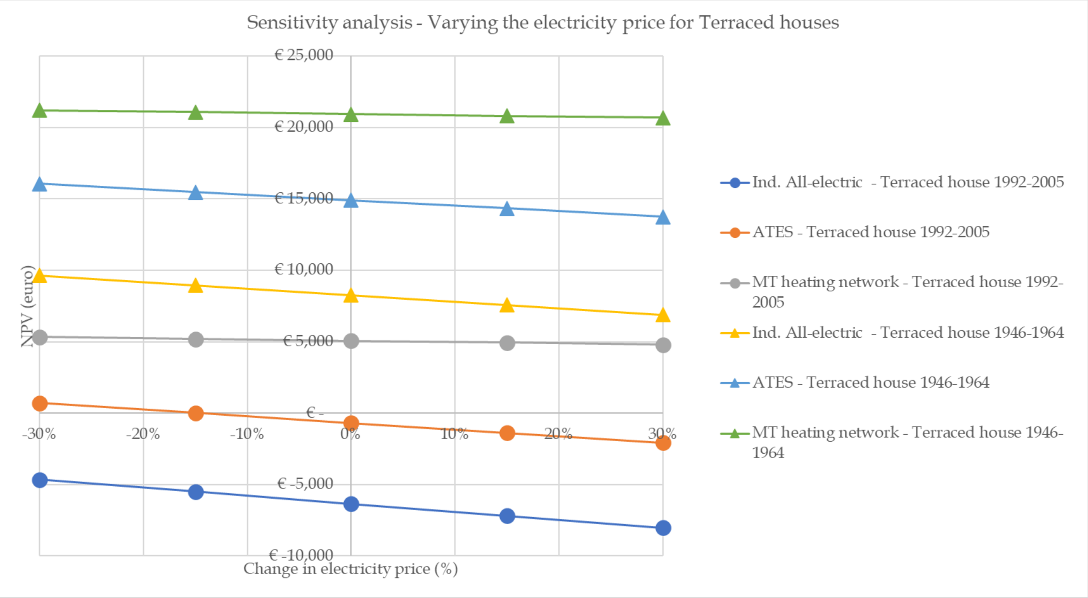


Figure 21 Sensitivity analysis – The effect on the NPV by changing the electricity price for Terraced houses

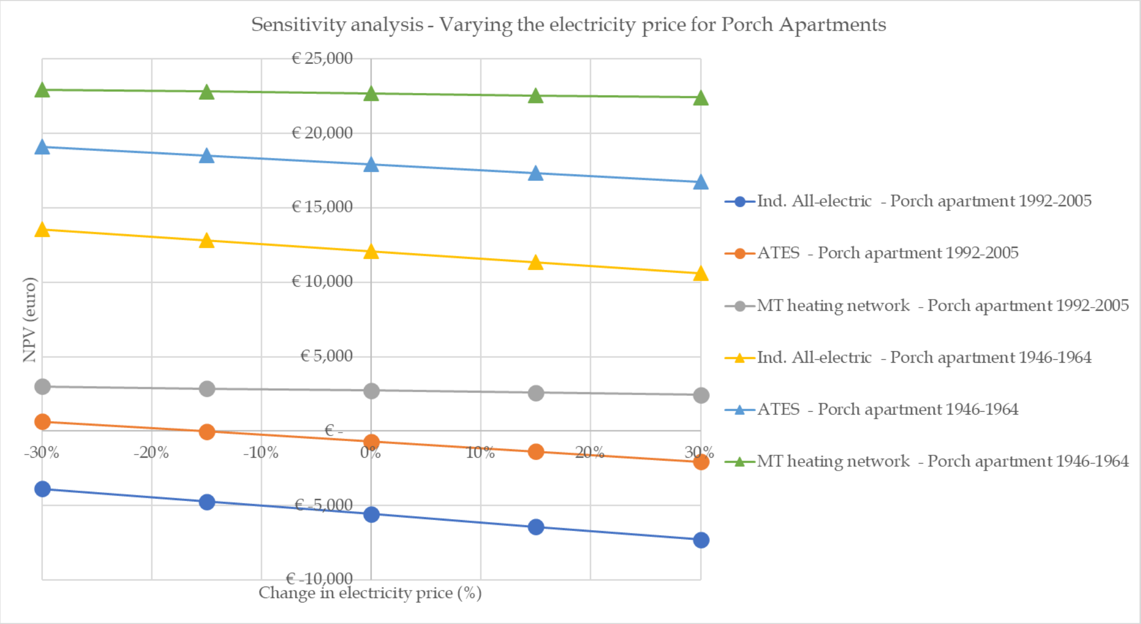


Figure 22 Sensitivity analysis – The effect on the NPV by changing the electricity price for Porch apartments

Figure 23 and Figure 24 show that the LCOE increases by a higher price for electricity. The alternative heating scenarios are more affected by a change than the reference scenario. The scenario that is most affected is the ATES scenario for terraced houses 1992-2005 (grey line in Figure 23). An increase in LCOE from € 156 to € 199 per MWh is noticed when the electricity price increases which equals an overall change of 22%. Followed by the individual all-electric scenario (orange line in Figure 23), which changes from € 191 per MWh to € 238 per MWh and equals a 20% change. The MT-heating network is less affected by a change in the electricity price, for example in Figure 24 (yellow line, change 18%). Less electricity is used in these scenarios and thus becomes less affected by a change in electricity price.

Comparing the reference and ATES scenario with the building period 1992-2005 for both housing types, Figure 23 and Figure 24 show that the point of intersection between these two scenarios for the housing types differs. For terraced houses, the intersection takes place at a 15% lower electricity price compared to the standard value, while for porch apartments this intersection takes place at the standard value (0% change in electricity price). The difference between the LCOE of the reference scenario and the ATES scenario for porch apartments at a 30% lower electricity price is relatively bigger compared to the difference for terraced houses. The lower LCOE is caused by the larger energy demand for porch apartments and this relatively smaller difference between the two scenarios leads to the smaller intersection point for terraced houses than for porch apartments.

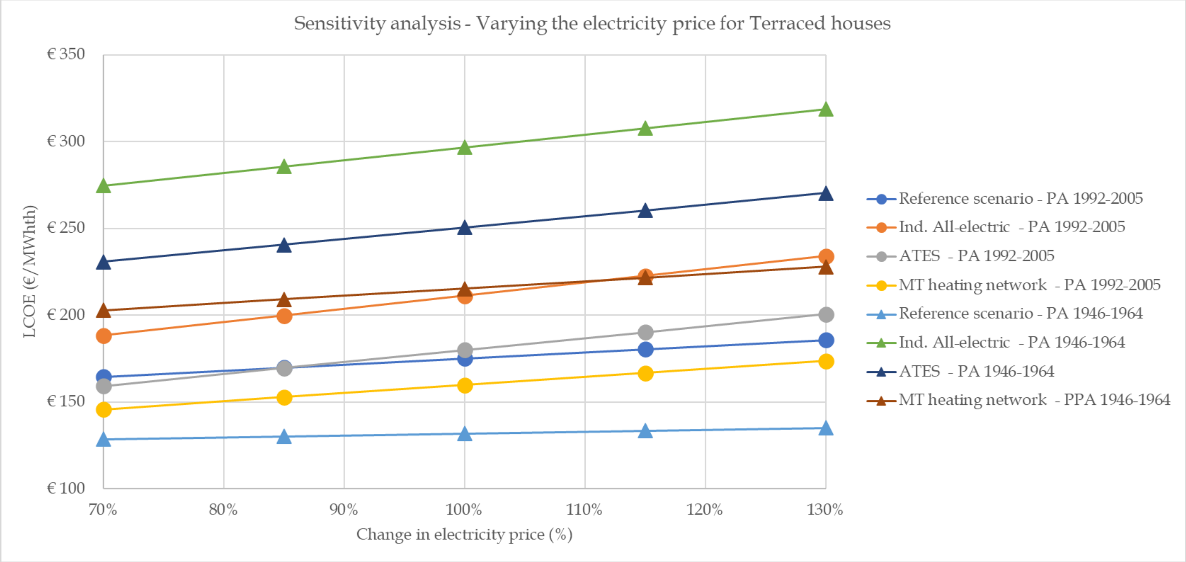


Figure 23 Sensitivity analysis – The effect on the LCOE by changing the electricity price for Terraced houses

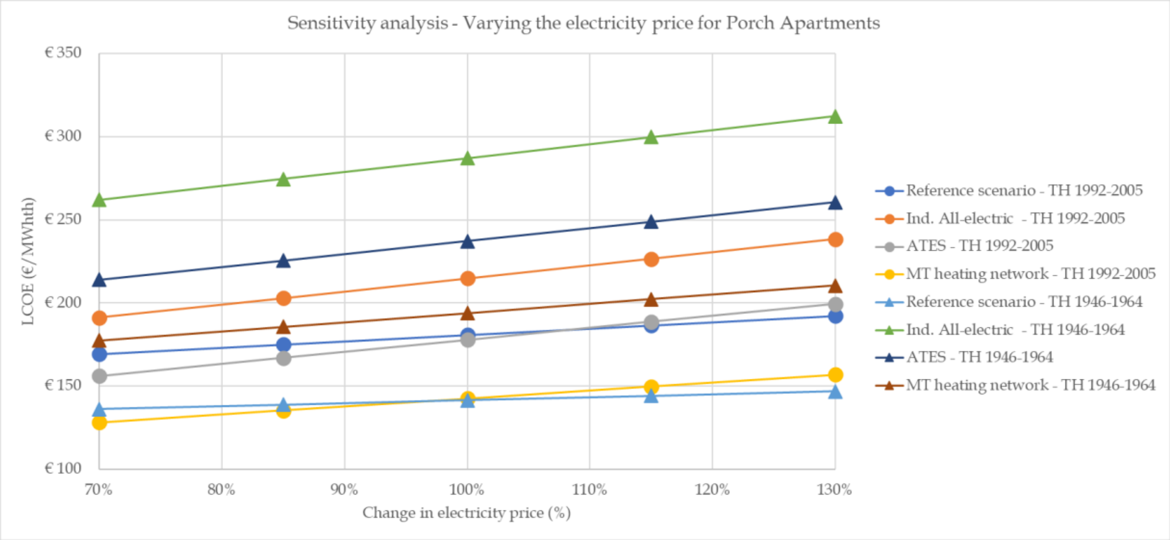


Figure 24 Sensitivity analysis – The effect on the LCOE by changing the electricity price for Porch apartments

4.4.2 Varying the heat demand

A third sensitivity analysis is performed in which the effect of a change in heat demand has been investigated. When comparing the different NPVs for the four different housing types and the scenarios one can notice relatively large changes in NPVs between an increased and decreased heat demand for buildings built between 1992-2005 (see Figure 25 and Figure 26).

Overall, a higher heat demand leads to a higher NPV. The ATES and MT-heating network scenarios are more affected by a change in heat demand (see the green and dark blue line in Figure 25). An increased heat demand leads to higher investment costs as the capacity of different parts in the scenario must be strengthened, while for the individual all-electric scenario only a capacity improvement for the ASHP is needed. Furthermore, this difference can be explained by the fact that a higher heat demand leads to more fuel costs, in particular for the reference scenario. In addition, the alternative heating scenarios are less affected as they have lower fuel costs.

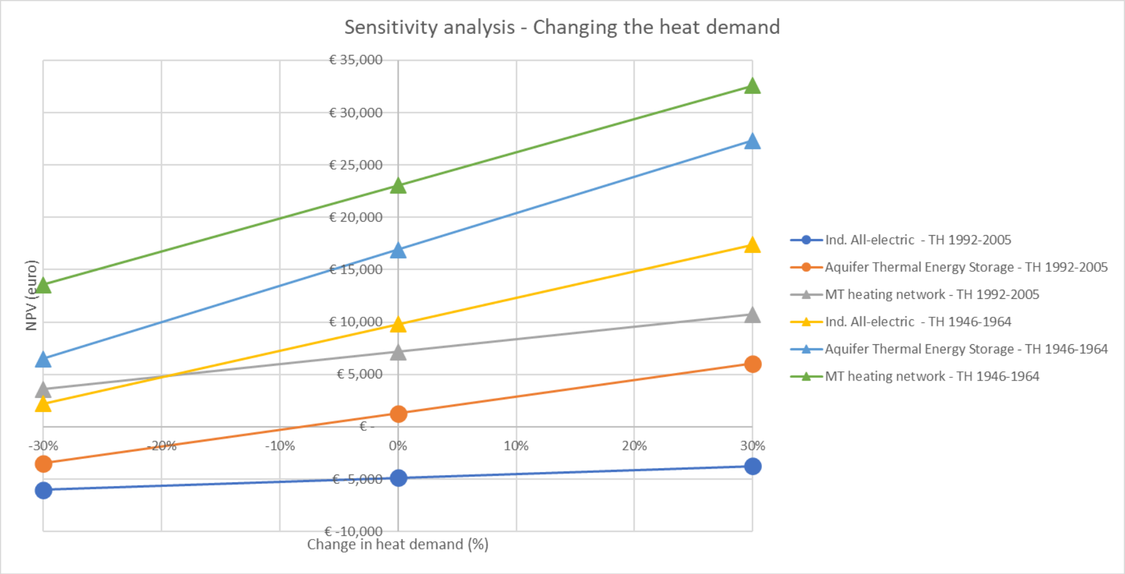


Figure 25 Sensitivity analysis - NPV for a Porch Apartments by changing the heat demand for the scenarios

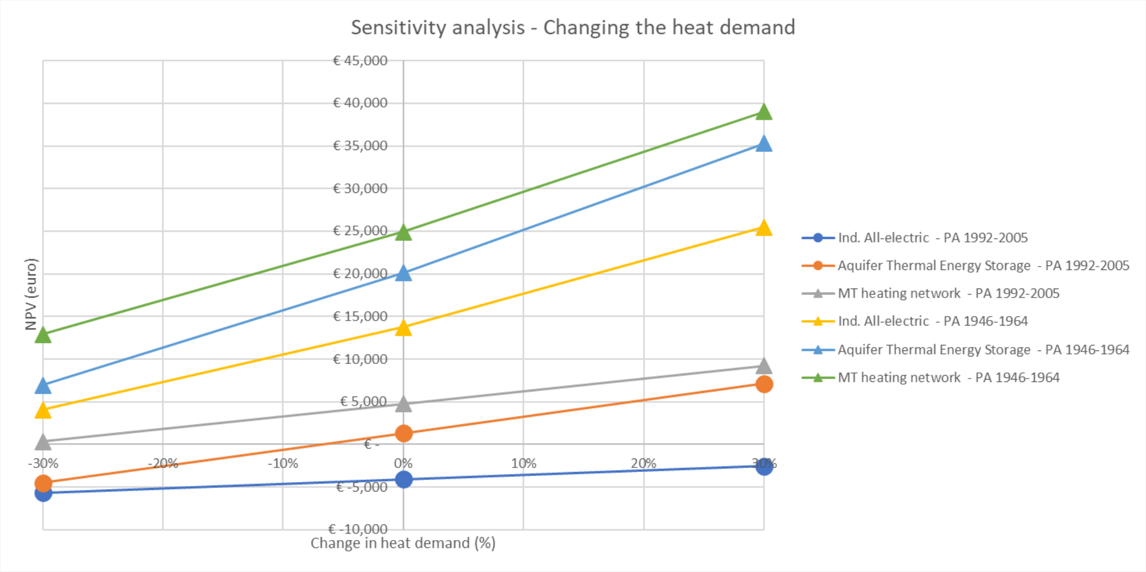


Figure 26 Sensitivity analysis - NPV for Terraced houses by changing the heat demand for the scenarios

Second, the effect on the LCOE is identified after varying the heat demand (see Figure 27 and Figure 28). The alternative heating scenarios are more affected than the reference scenario when varying the heat demand. In general, an increase in heat demand leads to a decrease in LCOE. The dark blue line in Figure 27 Figure 25shows that the ATES scenario is most affected by a change in heat demand (39%), followed by the MT-heating network scenario that changes 33% (dark red line in Figure 27). The individual all-electric scenario is the alternative heating scenario that is affected the least with 21%, whereas the smallest change is represented by the reference scenario (7%) as is indicated with a light blue line in Figure 27. The higher heat demand leads to relatively more investment costs in the collective scenarios compared to the individual all-electric and reference scenarios. In addition, relatively lower changing fuel costs for the ATES and MT-heating network scenarios lead to a steeper decrease in LCOE, compared to the reference and individual all-electric scenario.

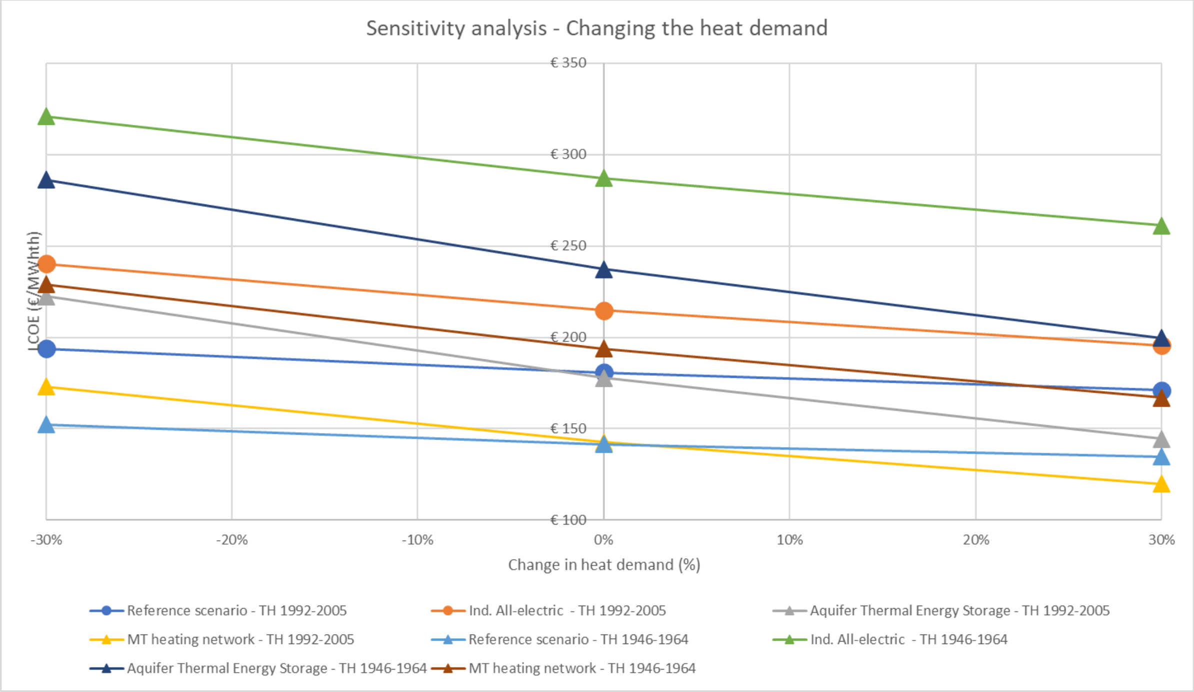


Figure 27 Sensitivity analysis - varying the heat demand for Terraced houses and for the scenarios

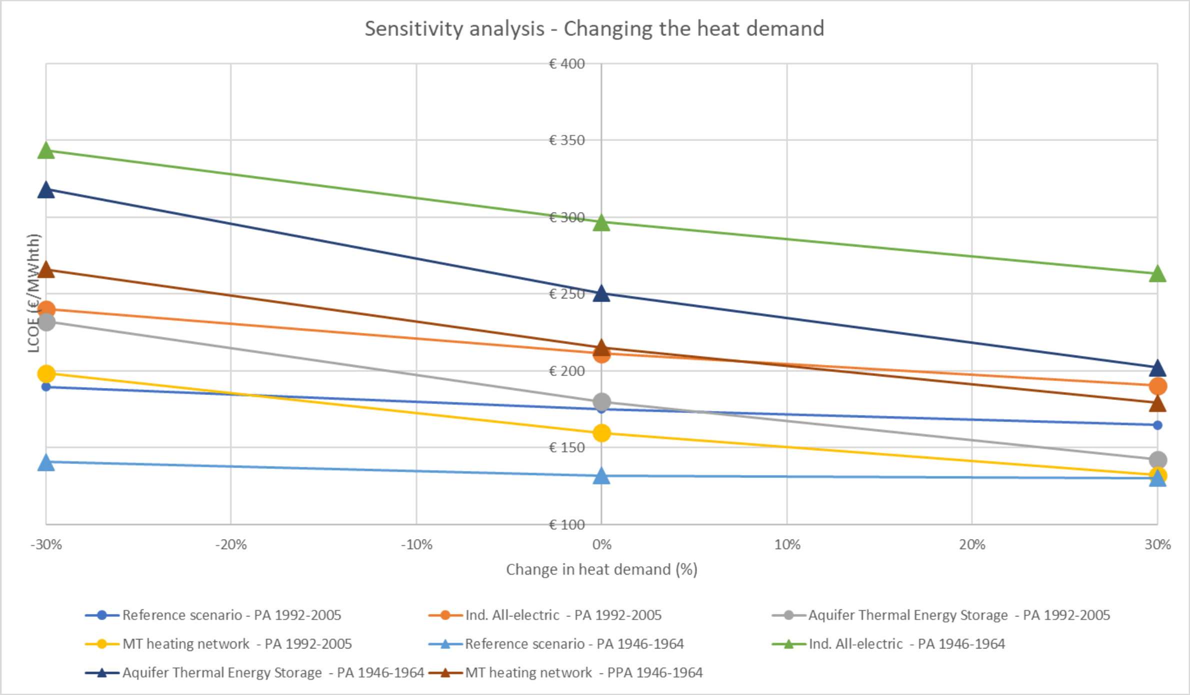


Figure 28 Sensitivity analysis - varying the heat demand for Porch Apartments and for the scenarios

To summarize, the main impacts of the sensitivity changes are:

- First, the LCOE increases and NPV decreases for all scenarios by increasing the price of electricity. The alternative heating scenarios are more affected than the reference scenario. The individual all-electric and ATES scenarios are most affected by a change in electricity price, caused by the usage of electricity.
- Second, the sensitivity analysis shows that an increase in discount rate leads in general to lower NPVs and higher LCOE and that the MT-heating network and ATES scenario are strongly affected by a change in discount rate due to the relatively higher investment costs and future cash flows.
- Finally, when varying the final energy demand the NPV and LCOE for all scenarios are highly affected. An increased energy demand leads in general to a higher NPV and a lower LCOE. The MT-heating network and ATES scenarios are less affected compared to the reference and individual all-electric scenario, as they have lower fuel costs.

5. Discussion

From the modelling results, it is clear that almost all alternative heating scenarios for the two analysed housing types built between 1946-1964 are economic and environmentally more profitable compared to the competitive natural gas reference scenario and that almost all alternative heating scenarios for the two analysed housing types built between 1992-2005 are profitable. This research adds to current theoretical insights by adding the created methodology, as well as with the developed results, as it performed an economic and environment end-user analysis for alternative heating scenarios that cover the literature gap.

5.1 Scientific implications

5.1.1 Contributions of the developed methodology to scientific literature

To start with, the created methodology for this research contributes to the current methodologies in three ways. Firstly, in current techno-economic models, the end-user perspective is often seen as the missing link within current research on relatively small spatial areas (Häkkinen et al., 2019; Van der Molen et al., 2018). However, as described in the introduction, hardly studies have been conducted to identify the costs and profits at the building level for different measures and technologies (Netherlands Enterprise Agency, 2011; Amstalden et al., 2007; Wang, 2018). The incorporation of these technologies into a techno-economic model for a specific housing type and end-user in the Netherlands did not exist. To address this problem, this study created a methodology that is specifically focused on the individually end-user level after applying different alternative heating scenarios. This methodology also allows us to compare the collective and individual energy generation techniques and defines the economic and environmental attractiveness via the heat demand and CO_2 emissions, NPV, and LCOE. In addition, an important part of the distinction is the allocation of costs. This methodology describes a possible way in order to compare individual with collective energy generation technologies at the end-user level.

Secondly, the created methodology in this study is adjustable to any area, can filter data (e.g. housing type or building periods selection), easy adjustability of for example data parameters and finally this model is excel based, which is generically more convenient than programming software. However, programming software (e.g. Phyton or Matlab) has the advantage to adapt large databases, as this is key for the extension of the model with a larger address database, more technologies and housing types. Although the model is simplified, it offers a great chance for further elaboration even though the current limitations and perhaps implication in the Vesta MAIS model, as it offers new insights on a very specific end-user level.

Thirdly, even though existing models like Vesta MAIS and CEGOIA do consider the current insulation levels based on the building typology researched by the Netherlands Enterprise Agency (2011), the corresponding costs to increase the insulation are calculated via label jumps (e.g. D to A+) (Naber et al., 2016). However, these insulation costs are aggregated per housing type and even further aggregated per neighbourhood (Van der Molen et al., 2018), whereas the model created in this study calculated the insulation costs per building part and per house, which makes an individual building assessment easier. Therefore, it is possible to determine costs much more specifically at the end-user level, as costs are disaggregated per building part. In particular this is useful for existing buildings that partly applied already insulation.

Finally, a different methodology has been used to calculate the levelized costs. This study looks at the LCOE for several measures together, which ultimately forms the scenario all seen from an end-user perspective, while the study conducted by Wang (2018) looks at the LCOH for the heating technology itself. Second, the cumulative heat demand calculated in this study differs from the one used in the study of Wang (2018), as that study used an average heat demand value in order to calculate the LCOH, while this conducted study included a methodology, which calculates the heat demand per specific housing type. Therefore, this research adds to existing literature as it calculated the LCOE for an alternative heating scenario end-user perspective, which ensures to fully disconnect the building from the natural gas grid and the LCOE value is seen from the end-user perspective.

5.1.2 Contributions of the developed results to scientific literature

Furthermore, this research adds to the following existing findings in literature. First, the used methodology to calculate the current heat demand per housing type is compared to one existing research study and should be argued (Netherlands Enterprise Agency, 2011) (see Table 12).

Table 12 Heat demand validation in comparison the NEA (Netherlands Enterprise Agency, 2011)

Data validation	**Netherlands Enterprise Agency**	**Current heat demand**
	$m^3/100m^2$	$m^3/100m^2$
Terraced house 1946-1964	2,582	2,149
Terraced house 1992-2005	996	857
Porch apartment 1946-1964	1,761	2,726
Porch apartment 1992-2005	1,046	827

The values for terraced houses and new houses are aligned with the values found in other studies (Netherlands Enterprise Agency, 2011). On the contrary, old porch apartments are less aligned. Therefore, the chosen method to calculate the heat demand, which includes HDD, should be strongly argued, as it does not take into building specific properties (e.g. detached or adjacent apartments or heat gains). Instead, this method uses a standard base temperature (Janssens, et al., 2014). For example, all buildings are calculated as standalone-unit and are not considered adjacent to other buildings. However, this could considerably reduce the heat demand as higher outside temperatures could be used in the calculation, which reduce the heat demand. In most terraced houses only facades are adjacent to one or two other buildings, while for apartments the floor and roofs are also adjacent, depending of the position of the apartment in the total apartment block. This effect is also enhanced by the relatively low Rc-values corresponding with this building period and leads to even more increased energy transmission losses. Other studies instead used elaborated heat transmissions calculations, which do take into account the specific building characteristics (Netherlands Enterprise Agency, 2011; Netherlands Enterprise Agency, 2020). However, heat transmission calculations are more time consuming and complex, as a heat transmission calculation must be performed per house, taking into account all specific building characteristics. Even though, the heat demand for the old porch apartments is extreme, it was still insightful, because as it shows how the model reacts in stressful and extreme conditions. Also, this methodology showed that for other housing types the methodology to calculate the heat demand do function well, as the deviation is minimal.

Collective energy projects are often initiated by collaborations between citizens and companies. Since 2015, roughly 200 local energy service companies (ESCO's) exist in the Netherlands, which aim to generated and consume their renewable energy locally

(Hieropgewekt, 2015). These actors have different financial interest, which are often represented by three different financing models, namely: the fully public model, the public private partnership or private model (Rutz et al., 2019). In the fully public model, the investment is completely covered by the municipality or city. It has a lower internal rate of return and is covered by projects with a higher rate, which reduce the risk. The private model, seeks for maximization of the profits. The investment is privately done and is often used for heat suppliers and the end-user perspective. The public private partnership investors, participates in the designing, investing, building, owning and operating the energy supply system for a number of years. As this study focuses on the end-user, a private modelling approach has been used. However, changing the organizational modelling approach will affect the results, as many of the costs will then be allocated to different stakeholders with each have different financial interest and goals. A heat supplier aims for high profits and short payback periods, which increase the heat tariffs for end-users. Another modelling form is the cooperative private ownership. In this form citizens and companies invest together in the alternative collective heating system. This approach aims for relatively lower profits, which leads to a lower variable heat price for the end-user. This study has showed the economic and environmental impact of different alternative heating scenarios for end users, taking into account a private modelling approach. However, it would be recommendable to include also other forms of financing models in the model. This makes the model also suitable for other stakeholders, such as heat suppliers and municipalities.

This study adds to existing literature, as it calculated the LCOE for different alternative heating scenarios from an end-user perspective taken into account a specific end-user heat demand for different housing types. The results presented in this study add and confirms existing literature. For example, the results created by Wang (2018) are focused on one technology and used an average fixed heat demand. Although the used methodology differs from this study, results do show one similar trend to the study conducted by Wang (2018)as in both studies the lowest LCOE is for dwellings with the highest annual heat demand. However, this study also created new insights into existing literature and in particular to the results conducted by Wang (2018). For example, in general, all LCOE values calculated in this study do show higher values. For example, a medium heating network in this study is higher compared to the MT-heating network scenario in the study performed by Wang (2018). The researched LCOH in the study by Wang (2018) for a medium heating network is € 110 per MWh, which is lower compared to the results in this study (€ 140 per MWh to € 210 per MWh). As earlier is described in Section 5.1.1, this difference occurs, because this study incorporated a number of measures together and different energy demand has been used, while the study performed by Wang (2018) only focuses on the heating technology itself and used a fixed heat demand.

This study compared different collective heating alternatives on the economic perspective at the end-user level and therefore adds to existing literature. Lund et al. (2018), stated that the additional costs associated with the insulation requirements are a disadvantage for LT heating networks compared to the MT-heating networks. However, this study proved that even with insulation costs, the LCOE for the MT-heating network scenario is still cheaper varying between € 140 to € 210 per MWh and the ATES scenario between € 175 to € 250 per MWh. Although, Lund et al. (2018) did not cover all the same investments, which are considered in this study. For example, this study included an IBHP in the ATES scenario, which increases the investment costs by 10%. However, even without the IBHP, the ATES scenario is more expensive than the MT-heating network scenario. Østergaard et al. (2018) confirms these results and looked into the economic feasibility of IBHP and states that the costs are higher than the profits due to the relatively high investment costs.

Furthermore, this research has calculated the effects on the LCOE and NPV of a change in the discount rate, heat demand, and electricity price and therefore adds to existing literature. Wang (2018) performed a sensitivity analysis in which the effect on the LCOH is investigated after increasing and decreasing the heat demand by fifty percent. Comparing the two studies leads to a few interesting differences. Wang (2018) presented that an increase of 30% in heat demand leads to an 8% decrease and that a decrease of 30% in heat demand causes a 15% increase in LCOH of middle large heating networks, whereas this study shows a larger effect when the heat demand changes. With a higher heat demand, the LCOE for an MT-heating network for old houses decreases with 27%, and with a decrease in heat demand the LCOE increases with 15%. For newer houses, the effect is increased with 8%, as the heat demand forms a larger share of the total energy demand. As in this study, scenarios were analysed, which included extra measures as insulation, HDS, IBHP and includes extra energy demand for domestic electricity, warm tap water, and cooking, while in the study performed by Wang (2018) only a single technology and heat demand were investigated. Although both studies measured the impact of changing the heat demand, this study incorporated more aspects and looked at the end-user perspective.

5.2 Societal implications

The results provided in this research can be used as a starting point for the discussion on what technologies and measures should be favourable from the end-user perspective for different housing types. This research is useful as a guideline to perform economic analysis on the end-user perspective at a neighbourhood level and might be used by municipalities that want to inform end-users of the alternative heating options in order to speed up the heat transition. The costs are important in view of the willingness and financial support of owners and residents in order to fulfil actions (Wijngaart et al., 2014). In addition, the developed model contributes to this by personalizing the end-user situation in a transparent and clear manner. Furthermore, the impact for the end-user can be used as an input of discussion with other stakeholders, for example, housing associations, heat suppliers, municipalities, or grid operators.

Also, the produced results of this study can be used as a reference for houses with similar characteristics, as it is very likely these buildings will have the same economic and environmental results. However, note that the economic and environmental results, especially for collective scenarios, are highly affected by the specific situation of the location. This is especially useful for end-users, municipalities, or heat suppliers in order to see what requirements the buildings need to meet in order to achieve economic feasibility within the projects. Thus, the general conclusions for the different housing types and their characteristics can be used.

5.3 Limitations and suggestions for improvement

First of all, it should be noted that the techno-economic database used in the model is deducted from average values. Average values are very liable to changes, either upward due to neglected costs in reference projects or downward due to further development of a technology (Blok et al., 1993). Therefore, the economic analysis for end-users are only an indication, despite the fact that they are identified for specific housing types and further characteristics.

Secondly, another point of attention is to consider the future development of techno-economic parameters, such as costs of technologies and technical improvements. Usually, the price of technologies decreases due to the doubling of the total quantity of items produced, which is commonly represented by the experience curve (Wene, 2000; Jakob et al., 2004). However, this concept has not been included in the model as current reinvestments are equal compared to the costs of 2020. Furthermore, no technology improvements are considered. For example, an increased COP value for heat pumps or heat reduction losses in heating networks in upcoming years. Technology improvements lead to a reduction in energy input and an increased energy output. However, the used energy demand in this study is assumed to remain equal to the end of the modelling period.

Third, the current condition of the model is practically not yet applicable for a neighbourhood with a diversity of housing types, because the model only includes terraced houses and porch apartments. However, there are other typical Dutch housing types, such as detached houses, gallery flats and semi-detached houses (as identified as in Chapter two). However, for a representable model, the methodology must be applied to these remaining housing types.

Fourth, He (2019) showed the importance of investment decision making optimisation of energy efficiency retrofit measures for multiple buildings, however this research assumed that all investments were done in the first year. Applying investment decision making optimization may lead to an increased financial benefit for the end-user, as it might save more costs or lead to higher profits. A good addition to the current model is to implement this investment decision making optimisation tool, as end-user are then informed about various investment possibilities taken into account the time.

Fifthly, the energy generation systems for the collective scenarios are currently calculated with several assumptions. However, the profitability of collective energy generation systems are location and project specific (Pusat et al., 2014). For example, all additional transmission lines extending from the heat source affect the technical requirements, such as the length of pipelines, number of pump stations, heat loss calculations, supply and retour temperatures, pipe diameters and fluid velocity (Pusat et al., 2014; Joelsson et al., 2009). Also, not every location offers a promising heating solution, as the financial potential for MT and LT heating networks is in any case dependent on the availability of the heat source and corresponding heat demand (Ministry of Environment and Energy, 2015). However, the model did not covered this part and thus is the economic feasibility of alternative collective scenarios questionable, although this can be changed manually in the model. Furthermore, the model does not take into account the spatial constrains of certain technologies. For example, heat pumps and heating networks requires major interventions and occupy substantial space. Especially in old neighbourhoods and houses, because often this contains narrow streets and relatively small buildings (Schepers et al., 2019). An addition to the current model would be to combine it with an geographical information system (GIS) model as the Vesta MAIS model already does, thus for example the infrastructure, heat sources and potential for alternative heating system are known and the model automatically calculates the most promising technologies.

Furthermore, results in this study are not fully aligned with other scientific studies that state that heating networks are not a very attractive business model commercially, as they have high investment risks and low financial returns (Hoogervorst et al., 2017). A study performed by Haffner et al. (2017) identified an average return on their project of 4.8 percent, whereas they also state that a reasonable return is between 5.1 and 6.6 percent. Instead, this study assumed that all costs are made by the end-user and that there are no financial limitations regarding the business cases.

Fifthly, this study used for all technologies the same private model approach, whereas in reality different stakeholders have different economic interests (Rutz et al., 2019). Even though several aspects of other financial models were included, such as higher or lower discount rates, as is elaborated in Section 4.4.1. However, the current private modelling approach did not cover for investing options (e.g. a mixture of own equity and loan capital), minimum profit margins and payback periods. Furthermore, the biggest scale-up of the heat transition does not only depend on the end-users, but depends on a collaboration between different stakeholders, for example heat suppliers, grid operators, municipalities and banks. This study assumed that all external factors such as permits, legislation, feasible business cases were all assigned and achieved by the end-user, however in reality an intensive cooperation between the different stakeholders is necessary to succeed the project.

In this study we assumed that no electricity grid reinforcements or connections, which are part of the buildings, were required to realise the alternative heating scenarios. Even though network operators must be able to supply sufficient capacity to households and that they are held ultimately responsible for any adjustments, it may be that building owners require an improvement of their electricity capacity, which normally leads to additional costs. According to the largest network operators in the Netherlands, these costs can rise considerably and take up a large part of the initial investments (Liander, 2020a; Stedin, 2020). Besides, a more severe connection leads to more costs and thus cuts both ways.

This research only investigates the economic attractiveness of the different scenarios for the housing types and defines optimal as lowest LCOE and highest NPV value. However, other potential benefits of the different technologies, for example the increased value of a building in case of increased insulation levels and more comfort, may lead to a different definition of what is seen as the optimal outcome. However, this study does provides valuable insights using the performed analysis of the heat demand and CO_2 emissions, the NPV and LCOE for different scenarios. A comprehensive way to assess all these aspects is to use a multiple-criteria decision analysis, that explicitly evaluates conflicting criteria in decision making.

Another uncertainty in the model are the used and incomplete input parameters. For example, modifying the commodity prices for natural gas and electricity lead to pronounced impacts on the results. Therefore, it is advised to create several price development pathways, as PBL did in the Climate and Energy Outlook 2019. However, this study only looked at a price variation of electricity, whereas other changes as tax, ODE or available subsidies also effects the outcome. Although, most of the Dutch subsidies such as SEEH, ISDE and SDE++ were part of the methodology, no future, local or European subsidies for individual and collective heat generation were used (Hieropgewekt, 2020). For example a heating network in Hengelo has received a subsidy from Europe for a heating network that uses bioenergy and residual heat (Intelligent Energy Europe, 2012). Also, no energy investment allowances were taken into account in this study, which yields an average benefit of 13.5% (IF technology, 2018).
Others, such as the CO_2 emissions factor for electricity has been assumed to remain equal over time. However, according to Wijngaart et al. (2017) it is expected that the emission factors for electricity will further decrease after 2030, due to the implementation of more sustainable energy in the energy system. Another point of discussion is the chosen emission factor for residual heat. In the methodology it has been assumed that residual heat does not have any emissions. However, some studies state that residual heat do emit CO_2 emissions, as the industries use fossil fuels to produce the heat (Milieucentraal, 2020). Other researches state that it is often difficult to determine how much CO_2 emissions must be allocated to the heat supplied by a heat network, which is especially the case with residual heat (CE Delft, 2020).

This study encourages to continue research on development of alternative heating scenarios seen from the end-user perspective, as is already partly identified. Three types of research topics are considered helpful to this academic topic:

1. Repeating this study taken into account the limitations discussed. Starting with improving the heat demand calculations by implementing heat transmission calculations. Followed by integrating different price developments as PBL has identified, expand the model with the other identified housing types as presented in Chapter two and connect the model to a GIS.
2. Perform a case study with actual energy data from a selected neighbourhood and compare this to the calculated values by the model, as this will increases the model validity.
3. Third, a large improvement is to extent the current methodology by implementing the remaining financial models (the fully public model and the public private partnership model). This leads to a more applicable and realistic model, as different stakeholders can calculate the end-user costs under different corporations.

6. Conclusions

To contribute to the transition towards a more carbon neutral heating system in the Netherlands and to aim for the goals of the Paris Agreement, this research investigated the economic and environmental impact of sustainable heating technologies at the end-user level for four different housing types by 2050, the following research questions was addressed: What is the economic and environmental impact of sustainable heating scenarios for the main existing housing types in the Netherlands up to 2050? In order to answer this, a new model was created and used for the analysis.

The identification of the most economic and environmental alternative heating scenario seen from the end-user perspective includes different phases. In the first phase, four scenarios were constructed: the reference, the individual all-electric, ATES and MT-heating network scenario. In the second phase the model is constructed with techno-economic parameters for individual building measures and individual (natural gas boiler and ASHP) and collective heat generation technologies (ATES and MT-heating network). Phase III contains the analysis part in which the heat demand and CO_2 emissions, NPV and LCOE for the identified scenarios were calculated. Finally, a sensitivity analysis is carried out that investigated the impact of a higher and lower electricity price, discount rate and heat demand on the NPV and LCOE.

The analysis showed that buildings without insulation measures built between 1946-1964 do have a much higher heat demand compared to the newer housing types built between 1992-2005. However, after validation of the heat demand of building period 1946-1964 with other performed studies the value for porch apartments deviate significantly, because the chosen method to calculate the heat demand does not take into account specific building characteristics. Whereas, the calculated heat demand for the building period 1992-2005 and terraced house 1946-1964 are validated and realistic compared to other conducted studies. Even though the latter do give matching results, the used methodology to calculated the heat demand for housing types in this study is arguable. The NPV for all alternative heating scenarios for the housing types built between 1946-1964 turn positive, whilst for housing types built between 1992-2005 only the MT-heating network and ATES scenario turn positive at the end of the modelling period. To answer the research question, the most economic and environmental attractive scenario seen from the end-user perspective is the MT-heating network as this scenario has the highest NPV, while the LCOE it depends on the housing type.

For older houses the reference scenario has the lowest LCOE, while for newer houses the MT-heating network scenario is favourable. Even though the ATES scenario has the highest initial investment costs, the lower fuel costs, subsidies and lower required reinvestments makes this scenario more favourable compared to the individual all-electric scenario as it results in a more attractive LCOE and NPV.

The sensitivity analysis proved that an increase in discount rate leads to a decrease in the NPV and leads to an increase in LCOE. Scenarios that are most affected are the ATES and MT-heating network scenarios, as these scenarios contain higher future cash flows. Also, a higher discount rate leads to an increase in LCOE. Varying the electricity price positively and negatively by 30 percent is not affecting the scenario preference, for either the NPV or the LCOE. However, this study identified that the NPV for the ATES and individual all-electric scenarios are most affected by an increase in electricity price, due to larger share of electricity consumption. Varying the heat demand highly affects all the alternatives scenarios and an increasement leads to a higher NPV and lower LCOE. The MT-heating network and ATES scenarios are less affected than the individual all-electric scenario, because they have lower fuel costs. Overall, the LCOE and NPV for the scenarios are highly sensitive to a change in discount rate and heat demand and less to a change in electricity price.

This research contributes to existing literature by the created methodology, which calculate the economic and environmental impact for individual and collective scenarios, in which the scenarios consist of a total package of measures required to disconnect entirely from the existing natural gas grid, for two different housing types from a private end-user perspective. Secondly, the created model and methodology offers new economic insights on a very specific disaggregated end-user level. Additionally, this research add to society as it can be used as reference for similar housing types, used as guideline to perform an economic and environmental assessment and as input of discussion with other stakeholders.

The main limitations of the methodology arise from the calculated heat demand, as the HDD do not take into account building characteristics, therefore or a representable value for the HDD per building type, or a more advanced calculation method, such as heat transmissions calculations needs to be considered. Furthermore, the research did not look into other potential benefits of the different scenario, for example the increased value of a building in case of increased insulation levels and more comfort, may lead to a different definition of what is seen as the optimal outcome. Also, this study did not look into learning curves and investment decision making for technologies while this is important for reinvestments. Many assumptions are made to calculate the costs for the collective energy generation technologies, for example no density and demand constraints and the availability of residual heat and ATES. Furthermore, this study only looked at the end-user interests, while the interest of other stakeholders such as heat suppliers, grid operators or municipalities were not taken into account. This study did not look into other possible scenario pathways of the development of energy and carbon prices.

To conclude, the current heating demand of the reference scenario is key to determine whether or not a scenario is profitable for the end-user. Investment, energy and O&M costs and lifetimes do vary between the different scenarios and influence the profitability of it. This model proved to be useful for a first environmentally and economically comparison of different alternative heating scenarios seen from the end-user perspective, although some major limitations require more attention to increase the applicability of the model. However, this research contributes to the current techno-economic and environmental future assessment of heating technologies at the end-user level.

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Appendices

- Appendix A: Energy prices and emissions
- Appendix B: Techno-economic model input
- Appendix C: Output used equations

Appendix A: Energy prices and emissions

Table A13 Variable natural gas costs excl. vat (Existing data for the years 2013-2019 is taken from CBS, 2020b and extrapolated taken into account Climate and Energy outlook 2019)

Variable Natural Gas costs in €/m^3 (Excl. vat)	**2020**	**2030**	**2040**	**2050**
Commodity price Natural gas €/m^3	0.35	0.31	0.27	0.22
Tax NG normal tariff (0-170,000 m3/yr) in €/m^3	0.33	0.48	0.66	0.84
ODE NG normal tariff (0-170,000 m3/yr) in €/m^3	0.08	0.09	0.09	0.09

Table A14 Variable electricity costs in the model (Existing data for the years 2013-2019 is taken from CBS, 2020b and extrapolated taken into account Climate and Energy outlook 2019)

Variable Electricity costs in €/kWh (Excl. vat)	**2020**	**2030**	**2040**	**2050**
Total electricity price (0-5,000 kWh/yr) in €/kWh	0.14	0.14	0.14	0.14
Total electricity price (20,000-50,000 kWh/yr) in €/kWh	0.118	0.11	0.09	0.08
Total electricity price (50 – 2,000 MWh/yr) in €/kWh	0.083	0.07	0.06	0.05

Table A15 Development of fixed electricity costs in the model (Existing data for the years 2013-2019 is taken from CBS, 2020b and extrapolated taken into account Climate and Energy outlook 2019)

Fixed Electricity costs in €/yr (Excl. vat)	**2020**	**2030**	**2040**	**2050**
0-10A (€/yr)	86	134	180	226
>10A -3 x 25A (€/yr)	212	250	289	328
>3 x 25A - 3 x 35A (€/yr)	797	906	1.009	1.112
>3 x 35A - 3 x 50A (€/yr)	1.158	1313	1.459	1.605
>3 x 50A - 3 x 63A (€/yr)	1.524	1722	1.908	2.094
>3 x 63A - 3 x 80A (€/yr)	1.885	2129	2.358	2.587

Table A16 Development of Fixed natural gas costs (Existing data for the years 2013-2019 is taken from CBS, 2020b and extrapolated taken into account Climate and Energy outlook 2019)

Fixed Natural gas costs in €/yr (Excl. vat)	**2020**	**2030**	**2040**	**2050**
0 -500 m^3/yr (€/yr	119	178	236	294
>500-4000 m^3/yr (€/yr	166	249	330	411
>4000 m^3/yr (€/yr	259	390	518	646

Table A17 Emission factors

Emission factor	Value	Unit	Reference
Electricity	0.53	kg CO_2 per kWh grey electricity	Lijst emissiefactoren, 2020
Natural gas	1.89	kg CO_2 per m^3 natural gas	Lijst emissiefactoren, 2020
Residual heat	0	Kg CO_2 per GJ heat	Schepers et al., 2019

Appendix B: Techno-economic model input

Table B18 Ratio between surfaces (ratio is created and based on: Netherlands Enterprise Agency, 2011)

				Front and back wall				**Closed side wall**			
	Floor area	Flat roof	Incline roof	F&B Facade	Single glass	Double glass	HR ++ glass	Side Facade	Single glass2	Double glass2	HR ++ glass2
Terraced house<1945	54%	17%	55%	48%	7%	14%	0%	48%	0%	2%	0%
Terraced house1946-1964	54%	0%	66%	49%	7%	17%	0%	61%	0%	2%	0%
Terraced house1965-1974	49%	0%	62%	38%	4%	20%	0%	55%	0%	2%	0%
Terraced house1975-1991	48%	0%	65%	38%	3%	15%	0%	55%	0%	2%	0%
Terraced house1992-2005	49%	49%	0%	44%	0%	6%	13%	52%	0%	0%	2%
Porch apartment<1945	100%	107%	0%	56%	9%	14%	0%	39%	0%	2%	0%
Porch apartment1946-1964	100%	109%	0%	54%	4%	22%	0%	35%	0%	2%	0%
Porch apartment1965-1974	100%	106%	0%	54%	2%	24%	0%	33%	0%	2%	0%
Porch apartment1975-1991	100%	117%	0%	49%	0%	18%	0%	33%	0%	2%	0%
Porch apartment1992-2005	100%	111%	0%	53%	0%	20%	0%	31%	0%	2%	0%

Table B19 Energy label, Warm tap water demand, cooking demand and factor space heating per housing type (Netherlands Enterprise Agency, 2011; Schepers et al., 2019)

Housing type and building period	**Energy Label**	**Warm tap water demand**	**Cooking demand**	**LT Collective system capacity**	**MT Collective system capacity**	**Factor Space heating**
	[-]	GJ/m^2 year	GJ/year	kW	kW	Percentage
Terraced House<1945	G	7,1	1,2	6	7	58%
Terraced House1946-1964	F	6,35	1,2	6	7	72%
Terraced House1965-1974	E	7,3	1,2	6	7	76%
Terraced house1975-1991	D	7,3	1,2	6	7	94%
Terraced house1992-2005	C	7,7	1,2	6	7	89%
Porch Apartment<1945	F	4,95	1,2	6	7	58%
Porch Apartment1946-1964	E	5,3	1,2	6	7	72%
Porch Apartment1965-1974	D	5,55	1,2	6	7	76%
Porch Apartment1975-1991	C	5,5	1,2	6	7	94%
Porch Apartment1992-2005	B	5,7	1,2	6	7	100%

Table B20 Domestic electricity consumption per housing type (Milieucentraal, 2020; Netherlands Enterprise Agency, 2011)

Building year	**Surface house**	**Average Electricity use per two persons** $(\boldsymbol{f}_{i,t})$	**Average electricity per person**	**Number of family members** $(\boldsymbol{fm})$
Years	m2	kWh/year	kWh/year	No.
Porch Apartment1946-1964	<100	2280	1140	2,2
Porch Apartment1992-2005	<100	1640	820	2,2
Porch Apartment1946-1964	100-150	2830	1415	2,2
Porch Apartment1992-2005	100-150	2830	1415	2,2
Porch Apartment1946-1964	>150	3950	1975	2,2
Porch Apartment1992-2005	>150	3950	1975	2,2
Terraced house1946-1964	<100	2860	1430	2,8
Terraced house1992-2005	<100	2860	1430	3
Terraced house1946-1964	100-150	3290	1645	3
Terraced house1992-2005	100-150	3340	1670	3
Terraced house1946-1964	>150	3950	1975	3
Terraced house1992-2005	>150	3950	1975	3

Table B21 Techno-economic parameters (Schepers et al., 2019)

Type	**Investment costs**	**Efficiency SH**	**Efficiency WW heating**	**Lifetime**	**O&M**
(Costs are incl. installation hours and excl. Vat)	Fixed / var [Eur/kW]	COP/percentage	COP/percentage	years	Maintenance and service costs of initial investment
Natural gas boiler	€ 2,000	90%		15	2%
Individual air/water heat pump Fixed	€ 4,998	350%	220%	15	2%
Individual air/water heat pump Var	€ 410	350%	220%	15	2%
Individual booster heat pump incl. WW buffer tank fixed	€ 3,500		220%	15	2%
Collective Heat Pump var	€ 114	40		15	6.0%
TES fixed costs	€ 135,000	40			2%
TES var costs	€ 115	40		30	
Thermal energy from surface water fixed costs	€ 90,000			30	3%
Thermal energy from surface water var costs	€ 198			30	
HT Heat transmission station var	€ 114			50	6%
LT Heat Transmissions station var	€ 114			50	6%
Heat transmission substation (only if >615790 kW) var	€ 135			50	3%
LT distribution pipes		20%		50	5%
LT connection pipes		20%		50	6%
MT Transport pipes		20%		50	6%
MT distribution pipes		20%		50	5%
MT connection pipes		20%		50	6%

Table B22 Insulation costs (Netherlands Enterprise Agency, 2011; Loos van der, 2016)

Insulation measures	**Costs (excl. VAT)**	**Rc-value/U-value**	**Lifetime**
	euro inc.l inflation (2020)	W.M2/K	years
Floor	€ 24	2.53	50
Flat roof	€ 231	2.53	50
Inclined roof	€ 63	2.53	50
Facade	€ 25	2.53	50
Single glass	€ 166	1.8	50
Double glass	€ 170	1.8	50
HR++ glass	€ 336	1.8	50

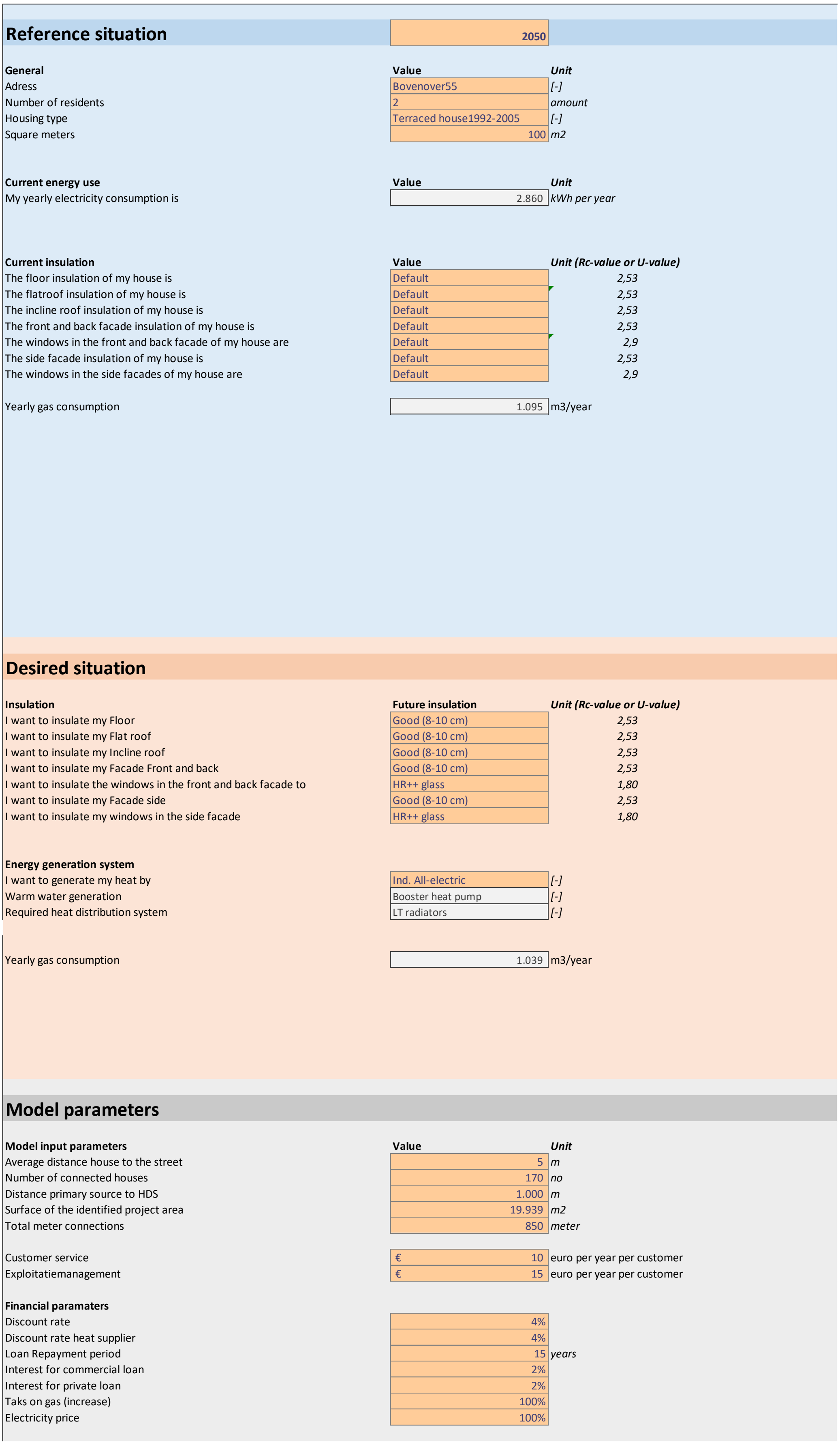
Table B23 Other techno-economic model parameters

Others	**Number**	**Unit**	**Ref**
Industrial residual heat (fuel costs pump)	0.0072	MJe/MJth	Netherlands Enterprise Agency, 2019
Individual heat pump Average full load hours	1650	hours	Schepers et al., 2019
Conversion factor MJ/m^3	31.65	m3/GJ	Netherlands Enterprise Agency, 2019
Emission factor Natural gas	1.89	kg CO2/ m3 natural gas	Milieubarometer, 2016
Conversion GJ to kWh	278	kWh/GJ	
Emission factor electricity	0.53	kg CO2/ kWh grey electricity	Milieubarometer, 2016
Gas connection removal Liander	€597.29	Eur/house	Liander, 2020b
Gas connection removal Stedin	421.96	Eur/house	Stedin,2020
Gas connection removal Enexis	€621.94	Eur/house	Enexis, 2020
Gas connection removal average	€547.00	Eur/house	-
Removing old furnace and installing electric furnace	1200	Eur/house	Natuur & Milieu, 2020c

Heating Degree Days (HDD)	2,500	K	KWA, 2020
Specific heat of air	1.01	kJ/kg*K	
Ventilation rate	3.24	m3/h/m2	
Density of air at 20C	1.23	kg/m3	
Floor Height	2.50	Meter	
Temperature inside (Tin)	19	Celsius	
Conversion GJ to MWh	0.277777778	GJ/MWh	

Table B24 Heating network system parameters (Netherlands Enterprise Agency, 2011 & 2020; Lensink et al., 2020)

Insulation subsidies	**Number**	**Unit**	**Lifetime in years**
SEEH floor (min Rd 3.5)	€ -7.00	Eur/m2	1
SEEH roof (min. Rd 3.5)	€-20.00	Eur/m2	1
SEEH facade (min. Rd. 3.5)	€-6.00	Eur/m2	1
SEEH HR++ glass (min. U 1.2)	€-35.00	Eur/m2	1
SEEH Triple glass (min. U 0.7)	€-100.00	Eur/m2	1
ISDE Individual air/water heat pump Fixed	€-1,900.00	Eur	1
ISDE Individual air/water heat pump Var	[-]	Eur	1
ISDE KA16279 2 kW	€-650	Eur	1
ISDE KA07872 kW	€-650	Eur	1
SDE++ thermal energy	€ 0.115	kWh/yr	15
SDE++ MT/LT heating network	€ 0.053	Eur/GJ	15
SDE++ electric collective Heat pump	€ 0.038	Eur/kWh	12



Reference situation 2050

General	Value	Unit
Adress	Bovenover55	[-]
Number of residents	2	amount
Housing type	Terraced house1992-2005	[-]
Square meters	100	m2

Current energy use	Value	Unit
My yearly electricity consumption is	2.860	kWh per year

Current insulation	Value	Unit (Rc-value or U-value)
The floor insulation of my house is	Default	2,53
The flatroof insulation of my house is	Default	2,53
The incline roof insulation of my house is	Default	2,53
The front and back facade insulation of my house is	Default	2,53
The windows in the front and back facade of my house are	Default	2,9
The side facade insulation of my house is	Default	2,53
The windows in the side facades of my house are	Default	2,9
Yearly gas consumption	1.095	m3/year

Desired situation

Insulation	Future insulation	Unit (Rc-value or U-value)
I want to insulate my Floor	Good (8-10 cm)	2,53
I want to insulate my Flat roof	Good (8-10 cm)	2,53
I want to insulate my Incline roof	Good (8-10 cm)	2,53
I want to insulate my Facade Front and back	Good (8-10 cm)	2,53
I want to insulate the windows in the front and back facade to	HR++ glass	1,80
I want to insulate my Facade side	Good (8-10 cm)	2,53
I want to insulate my windows in the side facade	HR++ glass	1,80

Energy generation system		
I want to generate my heat by	Ind. All-electric	[-]
Warm water generation	Booster heat pump	[-]
Required heat distribution system	LT radiators	[-]
Yearly gas consumption	1.039	m3/year

Model parameters

Model input parameters	Value	Unit
Average distance house to the street	5	m
Number of connected houses	170	no
Distance primary source to HDS	1.000	m
Surface of the identified project area	19.939	m2
Total meter connections	850	meter
Customer service	€ 10	euro per year per customer
Exploitatiemanagement	€ 15	euro per year per customer

Financial paramaters		
Discount rate	4%	
Discount rate heat supplier	4%	
Loan Repayment period	15	years
Interest for commercial loan	2%	
Interest for private loan	2%	
Taks on gas (increase)	100%	
Electricity price	100%	

Figure B29 Example of a filled in Model dashboard

Appendix C: Output used equations

$$CapEx\ end\ user\ reference\ scenario = CapEx\ NG\ boiler + CapEx\ HDS \qquad (euro) \qquad [26]$$

$$\begin{aligned}
&CapEx\ end\ user\ all.electric\ scenario\\
&\qquad = Inv.costs\ Fixed\ ASHP + \ Inv.costs\ VAR\ ASHP\\
&\qquad \cdot capacity\ ind.ASHP - Fixed\ subsidy\ ASHP\\
&\qquad + Inv.costs\ Booster\ HP - fixed\ subsidy\ Booster\ HP \qquad (euro) \qquad [27]\\
&\qquad + Inv.HDS_{LT}\ )\\
&\qquad + Inv.costsdisconnecting\ Gas\ connections\\
&\qquad + Inv.costs\ eletric\ cooking\ \ + Inv.costsi\ nsulation
\end{aligned}$$

$$\begin{aligned}
&CapEx\ end\ user\ ATES\ scenario\\
&\qquad = Inv.Booster\ HP - fixed\ subsidy\ Booster\ HP\\
&\qquad + Inv.HDS_{LT}\ ) + Inv.disconnecting\ gas\ connection\\
&\qquad + Inv.eletric\ cooking + Inv.insulation\\
&\qquad + \Bigg[(Total\ req.power_{LT} \qquad (euro) \qquad [28]\\
&\qquad \cdot (Var\ HTS + Var\ Coll.HP + Var\ HTS + ATES_{var})\\
&\qquad + Fixed\ coll.HP + Fixed\ ATES + Fixed\ TES\\
&\qquad + Inv.Distr.heating\ pipes\ LT\ ATES\\
&\qquad + Inv.connection\ pipes) \cdot \frac{q_{i,t}}{Q_{i,t}} \Bigg]
\end{aligned}$$

$$\begin{aligned}
&CapEx\ end\ user\ MT\ heating\ network\ scenario\\
&\qquad = Inv.HDS_{HT} + Inv.insulation\\
&\qquad + \Bigg[(Var.costs\ HTS \cdot Total\ required\ power_{MT}\\
&\qquad + Inv.Distr.heating\ pipes\ MT \qquad (euro) \qquad [29]\\
&\qquad + Inv.connection\ pipes\ MT + Inv.MT\ Transport\ piping)\\
&\qquad \cdot \frac{q_{i,t}}{Q_{i,t}} \Bigg]
\end{aligned}$$

$$Fuel\ costs\ reference\ scenario_{i,t} = \ Gasprice_t \cdot (WW\ demand \cdot Efficiency\ WW\ production + \ SH\ demand \cdot Effiency\ SH\ demand) \qquad (euro) \qquad [30]$$

$$Fuel\ costs\ ind. all\ electric\ scenario\ _{i,t} = Electricity\ price \cdot \left(\frac{WW\ demand}{COP\ Warm\ water} + \frac{SH\ demand}{COP\ space\ heating}\right) + fixed\ electricity\ costs \qquad (euro) \qquad [31]$$

$$Fuel\ costs\ ATES\ scenario_{i,t} = \ fixed\ energy\ costs_{i,t} + variable\ energy\ costs_{i,t} + \left[\left(\frac{\frac{Total\ req. power}{(1 - heat\ transport\ losses)}}{COP\ collective\ HP} + \left(Total\ req. powerx - \frac{Total\ req. power}{COP\ Heat\ pump\ system}\right) \cdot (Distribution\ pump\ energy\ heat + Distribution\ pump\ energy\ cold + Distribution\ pump\ energy)\right) \cdot \frac{q_{i,t}}{Q_{i,t}}\right] \qquad (euro) \qquad [32]$$

$$Fuel\ costs\ MT\ heating\ network\ scenario_{i,t} = \ fixed\ energy\ costs_{i,t} + variable\ energy\ costs_{i,t} + \left[\left(\frac{Total\ required\ power_{MT}}{(1 - heat\ transport\ losses)} \cdot 0.0072 \cdot \frac{\text{individual energy demand}}{Total\ energy\ demand}\right) \cdot \frac{q_{i,t}}{Q_{i,t}}\right] \qquad (euro) \qquad [33]$$

$$O\&M\ costs\ reference\ scenario_{i,t} = \ Inv. Natural\ gas\ boiler \cdot mf + CapEx\ HDS\ \cdot mf \qquad (euro) \qquad [34]$$

$$O\&M\ cost\ ind.all\ electric\ scenario_{i,t} = Inv.ASHP \cdot mf_{ASHP} + Inv.BHP \cdot mf_{BHP} + Inv.LT\ HDS \cdot mf_{LT\ HDS} \quad (euro) \qquad [35]$$

$$O\&M\ costs\ ATES\ scenario_{i,t} = inv.BHP \cdot mf_{BHP} + Inv.LT\ HDS \cdot mf_{LT\ HDS} + \left[\left(Inv.ATES \cdot mf_{ATES} + Inv.TES \cdot mf_{TES} + Inv.Coll.HP \cdot mf_{Coll.HP} + Inv.HTS \cdot mf_{HTS} + Inv.Distr.heating\ pipes\ LT \cdot mf_{heating\ network} + Inv.connection\ pipes\ LT \cdot mf_{heating\ network}\right) \cdot \frac{q_{i,t}}{Q_{i,t}}\right] \quad (euro) \qquad [36]$$

$$O\&M\ cost\ MT\ heating\ network\ scenario_{i,t} = Investment\ HT\ HDS \cdot m\mathrm{f} + \left[\left(Inv.HTS \cdot mf_{HTS} + Var.costs\ HTS \cdot Total\ required\ power_{MT} + Inv.Distr.heating\ pipes\ MT \cdot mf_{heating\ network} + Inv.connection\ pipes\ MT \cdot mf_{heating\ network} + Inv.MT\ Transport\ piping \cdot mf_{heating\ network}\right) \cdot \frac{q_{i,t}}{Q_{i,t}}\right] \quad (euro) \qquad [37]$$