Comparative analysis of potential district heating systems in older urban neighborhoods

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A case study in Benoordenhout, The Hague

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Abstract

The Dutch government has adopted ambitious targets to decarbonize the heat supply of the built environment. For this, key focus lies on building heat demand reduction and for the supply of renewable heat, a district-oriented approach is handled. For older urban neighborhoods, extensive building retrofits to reduce heat demand are often very expensive or legally restricted, making low-temperature heat systems unfeasible. District heating systems operating on a medium-temperature level (MT DH, ~70 ºC) can be a solution for such neighborhoods. Several potential heat sources for MT DH can be identified, such as heat from surface water (TEO) or wastewater (TEA) upgraded by large-scale heat pumps. Seasonal thermal energy storage in aquifers (ATES) can be used to improve the energy potential of these sources. Geothermal energy can also provide heat at the same temperature level. To assess and compare the district heating potential of these sources, a case study is performed on the district of Benoordenhout in The Hague. The heat demand of this district by 2030 was modeled using simulation data for different types of houses, under the assumption that only cost-efficient insulation measures are applied. The local heat potentials of TEO, TEA, ATES and geothermal energy were estimated using a range of tools. Data on capital and operational cost of heat technologies and DH infrastructure were obtained and integrated into an energy model, together with expected trends on prices of natural gas and electricity. Six heat scenarios were developed and compared to a reference scenario of individual gas boiler use. It was found that geothermal energy has the potential to cover the entire annual heat demand of Benoordenhout, and can be even larger by implementing a heat pump to the return flow. Connection to the cities' existing DH system is required to cover peak demand. The levelized cost of heat (LCOH) is found to be lower than for the reference scenario, and the project can yield substantial profits. The potential of TEO and TEA as heat sources for Benoordenhout is very limited. The LCOH in all scenarios is much higher than the reference LCOH, and the net present value (NPV) of the projects is negative. This is mainly due to high costs of DH infrastructure. TEO and TEA could become viable heat sources when DH infrastructure is already in place. For consumers, it is not financially attractive to connect to a district heating system under current regulations.

Preface

The completion of this thesis marks the last phase of my master's program Energy Science and the end of my academic career of six years at Utrecht University. This research was conducted over the period February to August 2020, during an internship at consultancy and engineering firm *Tauw*, as member of the team Energy Transition and under supervision of Dr. Beau Warbroek. Dr. Wen Liu of the Copernicus Institute of Sustainable development provided supervision of behalf of Utrecht University.

During my time as a student in Utrecht, I have been blessed with the opportunity to obtain an abundance of knowledge in the fields of energy, sustainability and innovation, as well as a wide range of organizational and analytical skills. Over this period, my drive to address the challenges that global climate change poses on society has grown deeper and ultimately motivated me to the writing of this research. The research process, in turn, has proven to be another precious learning experience for me, both academically and personally.

Several people made invaluable contributions to the process of this thesis, to whom I wish to express my sincerest gratitude. First of all, I would like to thank Wen Liu for her supervision during my research process, her insightful opinions and her critical reflection on my methods and written work. I would like to thank Beau Warbroek for his guidance of my internship at Tauw. I wish him all the best at his new research position at Twente University. I also thank Gerjan Wubs of Tauw for the countless online meetings we had, during which he shared with me fruitful discussions and relevant information. I thank Simon Bos of Syntraal and Rob Ligtenberg of Tauw for their expert insights into TEA and ATES technology. Lastly, I thank the people of team Energy Transition for my pleasant first acquaintance with a career in the field of sustainable energy.

Bas van der Veen
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List of abbreviations

ATES = Aquifer Thermal Energy Storage
CAPEX = Capital Expenditure
CHP = Combined Heat-Power
COP = Coefficient of Performance
DH = District Heating
HP = Heat Pump
HT = High Temperature
LCOH = Levelized Cost of Heat
LT = Low Temperature
MT = Medium Temperature
NG = Natural Gas
NPV = Net Present Value
OPEX = Operational Expenditure
SPF = Seasonal Performance Factor
TEA = Thermal energy from wastewater
TEO = Thermal energy from surface water
th = thermal
MW = Megawatt
MWh = Megawatt hour
Vesta = Vesta MAIS model
WSHP = Water Source Heat Pump
WWSHP = Wastewater Source Heat Pump
WWTP = Wastewater Treatment Plant

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1. Introduction

1.1 Societal background

On the 28th of June, 2019, the Dutch government presented its national Climate Agreement. This elaborate document brings forward sector-specific ambitions and targets to keep the Dutch greenhouse gas emission reductions in line with the international targets set by the Paris Agreement in 2015 (Climate Agreement, 2019). Besides the motivation to prevent potentially disastrous global climate change, the Dutch policy on fossil fuel abatement is driven by another calamity. The extraction of vast amounts of natural gas from the northern gas fields over the last decades has caused several minor earthquakes, damaging thousands of buildings in the province of Groningen (van Thienen-Visser & Breunese, 2015). Under persistent societal pressure, minister Henk Kamp ordered the Dutch natural gas producer NAM to reduce its extraction rate in Groningen by almost half, and by 2023, less than 5 billion m^3 will be produced, compared to over 50 billion m^3 in 2010 (Rijksoverheid, 2018).

The Climate Agreement and the phasing out of natural gas will have far-reaching consequences for the built environment in the Netherlands. For all 7 million homes and 1 million utility buildings that are currently reliant on natural gas for space heating and hot water supply, alternative heat sources need to be found. By 2030, the first 1.5 million homes will have to be transformed, which would lead to an estimated emission reduction of 3.4 Mt CO_2-eq. annually (Climate Agreement, 2019, p. 16). To tackle this enormous challenge, the government envisions a district-oriented approach. For each neighborhood, it needs to be investigated what the most optimal and feasible heating solution would be, depending on factors like construction year, building typology, spatial orientation, geographic location, ambient/waste heat availability and economic status of residents (Fonseca & Schlueter, 2015; Ma et al., 2012). For newer neighborhoods with relatively high insulation values (energy label >B), gas-free heating solutions like low-temperature district heating or heat pumps can be implemented without major renovations (Brand & Svendsen, 2013; Junghans, 2015). Older urban neighborhoods, however, can be more difficult to supply with sustainable heat, which is due to lower insulation values that hinder the utilization of low-temperature (waste)heat from the environment or from all-electric sources on household level (Junghans, 2015). Extensive retrofits to the building envelope are often required to reach satisfactory performance of an individual heat pump system (Nagy et al., 2014). From an energy-sustainability point of view, insulation retrofits to reduce heating demand are often suggested as first essential steps in the process of improving the energy efficiency of buildings, but building owners might be hesitative, or simply incapable, of bearing the large investment costs in building retrofits for energy savings (Ma et al., 2012; Stieß & Dunkelberg, 2013).

Barriers to the adoption of demand-reducing retrofits can thus slow the implementation of low-temperature sustainable heat sources. While efforts like subsidy schemes for insulation retrofits are in place to lower these barriers, it is also important to take into account the cost-effectiveness of measures to reduce heat demand (Becchio, 2013). Zvingilaite (2013) stresses this, as well as the importance of considering alternative methods of heat production in the process of realizing emission savings in the built environment (Wang & Holmberg, 2015).

In densely populated urban areas, district heating systems have been proven to be an effective means of collective heat supply (Lund et al., 2014; Werner, 2017a). The combination of high building density and older building envelope causes a high heat demand in a small area, which is ideal for the competitiveness of district heating, as the distribution of heat over longer distances is costly and inefficient (Persson & Werner, 2011; Unternährer et al., 2017). Furthermore, scale effects can improve energy efficiency compared to single home heating systems (Lund et al., 2014; Rezaie & Rosen, 2012). If district heating systems can be supplied at higher temperatures, they are particularly interesting for the older segments of the built environment. The benefit of these systems is that radical changes to the building envelope and internal heating system are, although still beneficial, not required for the technical functioning of the system (CE Delft, 2018a).

Many district heating systems already exist in the Netherlands, but those are often dependent on the presence of an industrial waste heat source or on fossil or biomass-fired CHP plants (RVO, 2018). Where these sources are not present, generation of heat for a larger collective of homes can be done by other means, for example with geothermal energy or by deployment of a large-scale heat pump, that can upgrade low-temperature heat from ambient sources like air, ground, water or sewage (Averfalk et al., 2017; Pieper et al., 2019; Sayegh et al., 2018). The potential of thermal energy recovery from surface -and waste water is found to be very large in the Netherlands and the utilization of all-electric district heating systems makes way for integration of renewable energy sources into the heating sector (Frijns, Hofman & Nederlof, 2013). In combination with thermal energy storage, the variability of these sources can be tempered. The implementation of large heat pump systems is therefore an important aspect of the Heat Roadmap Europe (Mathiesen et al., 2019).

David et al. (2017) demonstrated the great European potential for large-scale heat pumps for district heating, and showed that they could provide significant GHG emission reductions for the built environment. In the Netherlands, these systems are so far rarely implemented, but their utilization in various forms are among the potential strategies towards gas-free neighborhoods developed by PBL and ECW (ECW, 2019). Residents of older urban neighborhoods might have particular interest in heat delivery systems that are more compatible with their lower insulation value and current heat plumbing.

An example of such an older urban district is Benoordenhout in The Hague (Figure 1). This district is situated in the northeast of the city, and includes several neighborhoods, built between 1890 and 1970, with a total population of 13,855 (CBS, 2019). Most houses were built before the second World War, that is, in a time without any building energy regulations, which means that their original insulation level is minimal (label F-G), and upgrading to label A will likely be costly. Moreover, the district has a monumental status ('beschermd stadsgezicht'), which restricts the implementation of visible adaptations to the exterior of the buildings. However, many residents expressed the ambition to investigate how they can make their home, and Benoordenhout as a whole, more sustainable and less dependent on natural gas. A foundation called DuurSaam Benoordenhout (DSBH) was set up to develop an energy transition plan for the neighborhood and to inform residents on energy saving measures (DSBH, 2019).

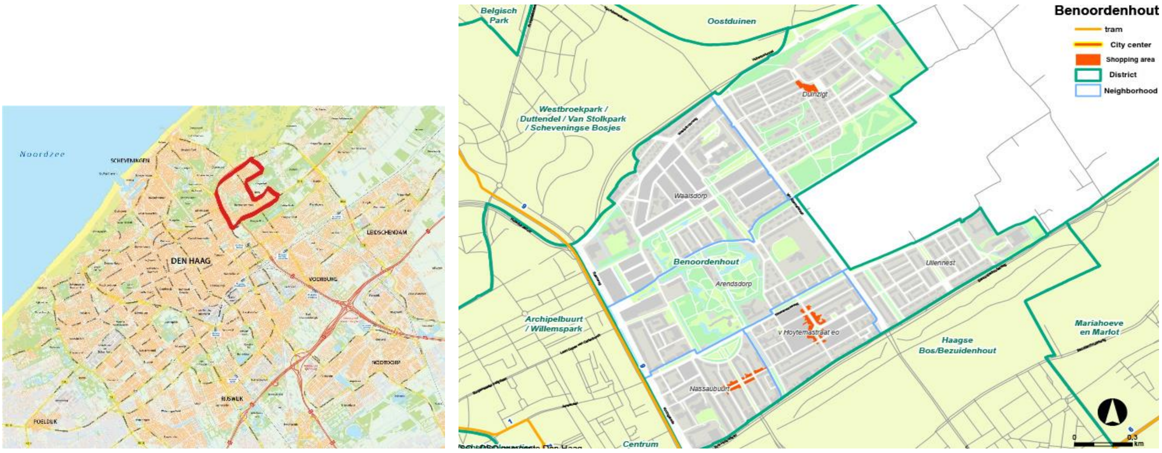


Figure 1a) Situation of Benoordenhout and 1b) District and neighborhood layout

The foundation approached consultancy firm Tauw to develop energy scenarios for individual or collective sustainable heating options. One of those scenarios could be a collective heat pump system that can upgrade low quality heat (15 ºC) to a supply temperature of a medium-temperature (MT) district heating network (65-75 ºC) (Schilling et al., 2019). This temperature is high enough to be used by older buildings retrofitted only with cost-effective insulation measures (RVO, 2020a). There are various potential sources for this low temperature heat, like surface water (TEO), surface ground or waste water (TEA) and depending on the source, seasonal thermal energy storage might be required to keep a balanced source load throughout the year. Another potential heat source for a MT district heating system for Benoordenhout is geothermal energy for direct heating purposes. The subsurface of the province Zuid-Holland is known to provide favorable conditions for geothermal energy extraction, and the municipality of The Hague plans to develop several geothermal in the coming years (Motion2040, 2018; TNO, 2020b). It is yet to be investigated what the perspective of these scenarios for Benoordenhout is, and this will be the focus of this study.

1.2 Scientific relevance and knowledge gaps

Considering the increasingly important role that is projected for both district heating and (large-scale) heat pumps, additional research into applications that combine these technologies is requisite. Many studies have been performed that looked into the utilization of low-temperature ambient heat sources as input for large-scale heat pumps for district heating, and most have found very promising results (Averfalk et al., 2017; Bach et al., 2016; Pieper et al., 2019; Popovski et al., 2019). However, the used heat sources and energy potential of these sources are highly location-specific, just as situational circumstances like building stock, existing DH networks, regulations and energy prices. This makes it difficult to generalize obtained knowledge, and local analysis must be performed to acquire accurate insight in the local applicability of large-scale heat pumps. Moreover, the combination of low-temperature heat sources with seasonal heat storage like *aquifer thermal energy storage* (ATES) is rarely considered in international literature, while this is a promising technology that is increasingly implemented in the Netherlands (Fleuchaus, Godschalk, Stober & Blum, 2019).

Relatively little research exists on the utilization of low-enthalpy geothermal resources, like in the region of Zuid-Holland, for residential district heating (Willems & Nick, 2019). Most research regarding geothermal energy for district heating focuses on deep geothermal energy to extract heat at temperatures above 100 ºC (Beckers et al., 2014; Daniilidis, Alpsoy & Herber, 2017). The extraction temperature of low-enthalpy geothermal sources is similar to the supply temperature of MT district heating, and the technology thereby enters the same playing field as the large-scale heat pumps. Both technologies are also part of the range of district-oriented strategies of the Dutch government, as can be seen in the strategy overview of PBL's Startanalyse Leidraad in Appendix 1 (Hoogervorst et al., 2019). A comparative study into the local heat potential and performance of large-scale heat pumps and low-enthalpy geothermal energy as sustainable heat sources for MT district heating is therefore highly relevant.

1.3 Research objectives and questions

The goal of this study is to identify the best suited gas-free collective heating system for an older urban neighborhood, by analyzing and comparing the techno-economic performance of three district heating options, as well as the practical implications that each of the systems will have. This is done on the basis of a case study of the city district Benoordenhout in The Hague, consisting of several neighborhoods with predominantly pre-WWII residential buildings. The construction of district heating infrastructure, which is currently not in place, is accounted for as well. Benoordenhout can serve as an example for other older urban neighborhoods in the Netherlands, as many districts built in the same period are quite similar regarding characteristics such as urban density, insulation values and current demographic.

The collective heating options that will be assessed are:

- Medium temperature district heating by thermal energy from surface water (TEO) with a collective heat pump paired with seasonal aquifer thermal energy storage (ATES).
- Medium temperature district heating by wastewater thermal energy (TEA) with a collective heat pump, potentially paired with ATES.
- Medium temperature district heating from a local geothermal source, potentially paired with heat recovery by a heat pump system.

The heating systems will be compared to a reference scenario, in which all buildings will continue to use their current natural gas boilers. All scenarios, including reference, will assume cost-effective improvements to the building envelope before the starting year 2030, in line with expected trends. The three district heating technologies were chosen with guidance of the team at Tauw working on the Benoordenhout project, who did a preliminary analysis of the heating options for the district. Furthermore, the strategies from the *Startanalyse* by PBL and ECW served as guidance for the potential heating options (ECW, 2019). Other heating options, like ground source heat pumps are difficult to implement in dense urban areas. A district heating system based on industrial waste heat is not possible for Benoordenhout, due to a lack of suitable sources nearby (Gemeente Den Haag, 2014; RVO, 2020b).

To determine which of potential collective heating systems is best suited in terms of households served, heat costs, economic viability and emission savings, various technical parameters like source temperature and volume, delivery temperature, technology costs, heat demand and network size, but also external factors like electricity mix have to be determined. The main research question will therefore be as follows:

How to identify the best suited collective heating system for an older urban neighborhood, in terms of resource availability and economic and environmental performance?

This question will be approached by answering the following sub-questions:

Q1. What are the demand characteristics of the buildings in Benoordenhout?
Q2. What are the potential of alternative heat sources and techno-economic characteristics of the related heat supply technologies?
Q3. How to develop the heating system model to balance demand and supply for the three heating systems?
Q4. What are the energy, greenhouse gas savings and costs of each system compared to the reference scenario?

This research will focus on the heating system of the district of Benoordenhout, which can function as a case example of a Dutch urban neighborhood built before 1945. However, to integrate the heating systems in the larger energy system, the geographical scope needs to include at least the urban region of The Hague, and even the entire province Zuid-Holland. The temporal scope in which the energy transition for the built environment in the Netherlands will take place is up to 2050, but the first steps towards gas-free heating will be taken before 2030 by proactive neighborhoods like Benoordenhout. For the analysis of the heating options, it is assumed that construction of the measures will take place between 2025-2030 and that the systems will be operable from 2030 onwards. The economic and environmental analysis will be performed up to 2050, although the technical lifetime of some involved technologies will stretch beyond 2050. Estimations on price developments of natural gas and electricity and changes in emission factor of electricity will be taken up to 2050. With exception of the emissions resulting from electricity generation, only the emission savings of the use-phase of the technologies will be considered in this study. Emissions occurring during production, construction and end-of-life lie outside the scope of the study.

2. Technological background

In this chapter, a concise description is given of the physical working and practical implications of district heating and the proposed heat technologies, as well as an overview of relevant examples of state-of-the-art applications of the technologies.

2.1 District heating

2.1.1 Introduction to district heating

A district heating (DH) system is a shared heating system for multiple buildings, with one or multiple separate heat producers. The producers heat the energy carrier (often water/steam), which is then pumped around the district to be used by consumers. The used, cooler water is fed back into a return pipe to be heated again. DH systems have been used since the 19th century, and have since underwent a transition along 4 *generations* (Lund et al., 2014). The trend through these generations was generally a reduction in supply temperature: from steam, to high pressure water (>100 ºC), to water below 100 ºC and recently to even lower temperatures (40-70 ºC). Lower supply temperatures have the advantage that many different heat sources of lower quality can be used, such as waste heat from industry or data centers, or heat from the environment. Reduced supply temperatures also bring forward significant reductions in heat losses during transportation and distribution. Where the first generations of district heating could lose up to 50% of its thermal energy, 3rd and 4th-generation DH system lose about 5-30% (Lund et al., 2014;TKI Urban Energy, 2020). Besides a reduced supply temperature, 4th generation DH systems have several other distinctive characteristics. They can operate as *smart thermal grids* that involve more dynamic matching of supply and demand, multiple heat producers and prosumers on a single grid, storage of thermal energy and the integration of more renewable energy resources (Lund et al. 2014; Mazhar, Liu & Shukla, 2018). Some DH systems also facilitate the use of *district cooling* (Werner, 2017a, 2017b).

In order to move from the 3rd to the 4th generation of DH, connected buildings need to have a low heat demand per surface area, as well as a heating system than can transfer this low temperature heat effectively, like floor and wall heating (CE Delft, 2018b). In the Heat Roadmap Europe, the future pathway for sustainable heating of the European built environment is laid out (Mathiesen et al., 2019). In this pathway, district heating based on renewable resources will supply around 50% of all heat demand from the built environment.

The heat source(s) for a DH system can be a traditional energy producer, like a natural gas CHP plant, but also biomass, waste heat from industrial sources or data centers, geothermal energy or ambient heat upgraded by heat pumps. In the Netherlands, around 700,000 homes (8% of total) are connected to a DH network, most of which are fed by gas-fired CHPs, industrial waste heat and waste incineration (CE Delft, 2018a). In the coming decades, the Dutch district heating network is planned to be greatly expanded with other, more sustainable heat sources (see section 2.3).

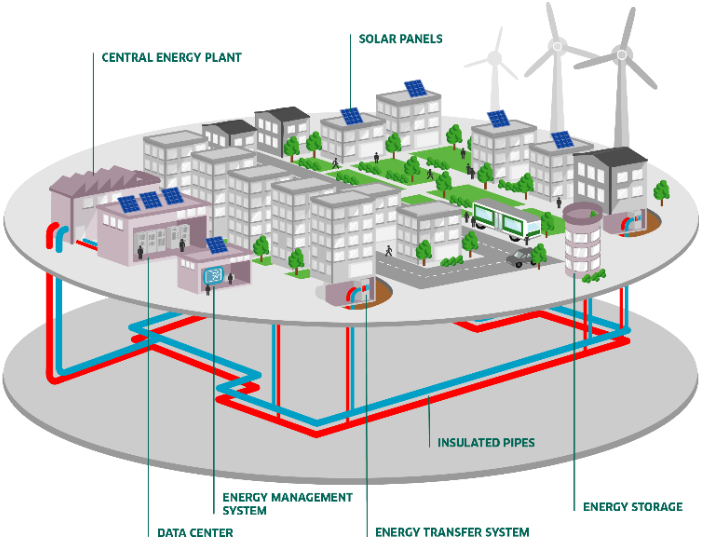


Figure 2: District heating system (From: Engie Services, 2020)

2.1.2 Cost of district heating

The cost of heat supplied by district heating can be divided into three main components:

- **The cost of heat generation**. These costs differ significantly per heat source. In case of waste heat utilization, generation costs are low, but when the heat source is installed specifically for the DH system, the costs of heat generation will be higher. DH heating systems based on CHP, geothermal energy or large heat pumps can have large investment costs (CE Delft, 2019). The fuel costs, if present, will depend highly on the heat source.
- **The cost of heat distribution**. These are the costs of bringing the heat from the production source to the end consumer, and consist mainly of infrastructural costs for pipelines and substations. The density of heat demand in the district is of high importance for the cost of heat distribution (Reidhav & Werner, 2008). DH systems in dense urban areas are generally more profitable as the transport distances are smaller, reducing infrastructure length and heat losses. However, due to the possible complexity of the system, initial investment costs of the distribution network can be large (Persson & Werner, 2011). Distribution costs are also much larger when the installation of distribution infrastructure takes place at a later time than the construction of the buildings themselves (Rezaie & Rosen, 2012). Other components of distribution costs are operation & maintenance (O&M) costs and costs due to heat and pressure losses, which form only a minor share (Persson and Werner, 2011).
- **Customer connection costs**. These costs depend on the measures that need to be taken on the property of individual consumers, to be able to connect to the DH system. This includes changes to in-home plumbing and a delivery set for tap water, but can in a broad sense also include the retrofit measures that need to be taken to prepare the building to the delivery temperature of the specific DH system. If the existing building envelope has poor insulative value, costly retrofit measures are required to be able to connect to a DH system with a supply temperature below 70 ºC (Hoogervorst et al., 2019; Ma et al., 2012).

The sum of these costs determines the total costs of heat supplied by a DH system and, given the total heat demand from the users, the costs per GJ heat delivered. However, the maximum cost of heat for the end-user are set by law in the Netherlands, so the total heat demand, the total number of end-users and the maximum price of heat determine the budget for the DH system operator (Autoriteit Consument & Markt, 2019).

2.1.2 District heating state-of-the-art

District heating is widely regarded as one of the key technologies to accomplish the shift to sustainable heating systems for the built environment (Lake, Rezaie & Beyerlein, 2017; Mathiesen et al., 2019). Collective heating systems can provide significant energy savings compared to single-building systems, but to achieve (nearly) carbon-free systems, new sustainable heat sources need to be applied and heat losses in distribution need to be minimized (Lake, Razaie & Beyerlein, 2017; Lund et al., 2014; Persson & Werner, 2011). Moreover, these new systems ought to be competitive with existing fossil-based heating systems (collective or individual) to minimize the cost increase for consumers and win market share. Many developments take place in the field of district heating, and some state-of-the-art examples are outlined below, as well as in sections 2.3-2.6.

The district heating system of Copenhagen is generally regarded as one of the most advanced and complete systems in the world (Bach et al., 2019; Mazhar, Liu & Shukla, 2018). The system serves 270,000 households and covers 98% of the cities heat demand. It is an open source network, to which many different actors can supply heat. Heat sources include natural gas and biomass CHPs, but also a geothermal source. The Danish government aims to make the energy supply for buildings fully based on renewable sources by 2035. The main transmission temperature is 95-120 ºC, but the temperature of many distribution grids is around 70 ºC. Especially for those lower temperature grids, lower-grade temperature sources could provide new input of renewable heat, based on geothermal energy or ambient heat upgraded by heat pumps. Heat pumps using seawater, sewage water, lake water and drinking water as heat source could supply 260 MWth, which would cover 10% of the winter peak demand of the city (Bach et al. 2019). By reducing the heat demand of buildings, more buildings can be supplied by MT DH and the cost of heat is lowered (Harrestrup & Svendsen, 2014). With these developments, the Copenhagen district heating system is moving towards the 4th generation (Lund et al., 2014; Mazhar, Liu & Shukla, 2018).

In the province of Zuid-Holland, the Netherlands, a state-of-the-art regional heat network is under development (Figure 3). This network is called the *Warmterotonde* (Heat Roundabout), and its goal is to integrate the heat systems of the largest cities in the region and to connect large suppliers and consumers of heat (Provincie Zuid-Holland, n.d.; Warm op Weg, n.d.). Vast amounts of waste heat are produced by the chemical industry in the harbor of Rotterdam, that cannot all be reused locally. Large consumers of energy are the residential district heating systems of Rotterdam, Den Haag, Leiden and Zoetermeer, the greenhouse horticulture industry and the Heineken brewery in Zoeterwoude. A large number of new and existing geothermal wells will be connected to the network, to exploit geothermal potential of the region in a coordinated and strategic manner (Provincie Zuid-Holland, n.d.). Furthermore, the Heat Roundabout will include underground storage heat at low and high temperatures (ATES and HT-ATES). In term, the network will become open source, so that competition between suppliers will lower the price of heat and give consumers a choice of heat provider (Provincie Zuid-Holland, n.d.; Schilling, Nikdel & De Boer, 2018).

A large district heating system is operated by Eneco in the district of Overvecht, Utrecht. Heat is supplied to 35,000 homes by two 180 MW gas-fired CHPs and a recently built biomass-fired CHP of 60 MW (Van Weeren et al., 2018). The supply temperature of the water is 72-95 ºC. To make this DH network more sustainable, it is planned to extract heat from a large wastewater treatment plant nearby and upgrade it to delivery temperatures with heat pumps (also see Section 2.3.2.2).

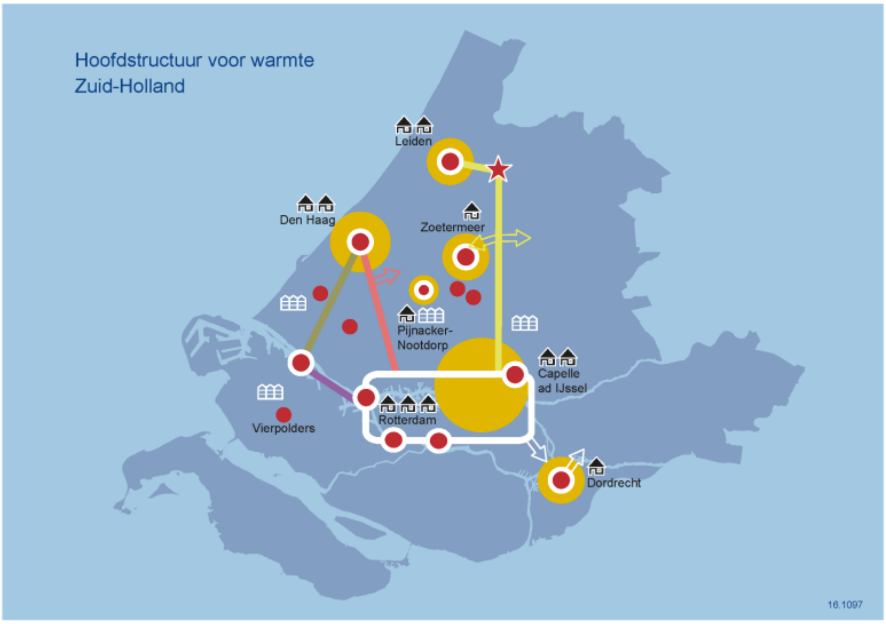


Figure 3: Map of the Heat Roundabout Zuid-Holland (from: Provincie Zuid-Holland, n.d.)

2.1.3 Deployment of collective heating systems

There are several important issues to consider in the deployment collective heating systems to replace individual heat systems. The main focus of this research is on the financial, environmental or technical concerns of these systems, but organizational and legal concerns are crucial for their deployment as well. Some of these concerns are highlighted below.

Existing district heating systems in the Netherlands are currently owned and operated by one party that produces the heat from one heat source. However, the future vision is that more open heat networks will be created, to which multiple parties can supply heat (Schilling, Nikdel & De Boer, 2018). For larger district heating systems with several actors, it must be clear which one party takes the leading role in the decision making process (Kleiwegt & De Coo, 2018). Furthermore, it is important to determine how the risk of the operation is spread among actors. For example, the high cost of geothermal energy in the research and development phase in combination with uncertainty regarding energy potential poses significant financial risks, that not many private parties are willing to take (Huculak, Jarczewski & Dej, 2015). For example, in the development of new geothermal sources for district heating in The Hague, energy company Eneco said that it is not willing to take full responsibility, but is willing to facilitate (Rijksvastgoedbedrijf, 2018). For such large investments with high associated risks, it is often required that a governmental party, either municipal, provincial or national, takes most financial liability. In case of the Heat Roundabout in Zuid-Holland, a fund was established to which the provincial government as well as the municipalities of Rotterdam and The Hague assigned millions of euros (Provincie Zuid-Holland, n.d.).

Social support for district heating and heat technologies like geothermal energy is crucial for the success of implementation. The social support of these technologies can be fragile, and negative experiences or reports can quickly damage the public opinion (Motion2040, 2018). There are several examples of failed district heating projects, like the ATES DH system in De Teuge, Zutphen (Megens, 2019). Moreover, the current coupling of natural gas price and price of district heating is increasingly debated, as gas prices have been rising and are expected to increase more in the coming decade (see also section 4.4). Because of this, consumers who made the switch to supposedly more sustainable district heating systems feel ‘punished’ by the higher taxes on natural gas, by which the maximum price of district heating also increases

(Consumentenbond, 2019; Woonbond, 2019). Moreover, the actual costs of connection to a district heating system are often much larger than the cost with a natural gas boiler, because of additional costs like the high initial connection fee and the renting fee for the delivery set, and changing heat suppliers is not possible (Stadsverarming, 2015). Several large advocate associations for consumers have issued an open letter to the Dutch minister of Economic Affairs and Climate, in which they state that they would dissuade consumers to switch to district heating, as long as there is no decoupled and fixed price for district heating (Woonbond, 2020). It is important that the social support for district heating is maintained, by taking common concerns of district heating user into consideration, and that similar problems are ruled out before operation of a new district heating system.

In the Netherlands, there is a legal right of access to energy, and it is therefore important that the heat supplier of a DH system can guarantee the heat supply at all times. To achieve this, the installation of backup heat supply, often in the form of natural gas boilers, is highly recommended and generally applied for both geothermal and heat pump driven DH systems (Kleiwegt & De Coo, 2018). The inclusion of back-up supply is an important aspect in DH system development and can be a significant cost factor of the system. Interconnecting adjacent DH networks can provide more security of supply as the pool of heat sources is increased, making the risk of malfunction smaller.

2.2 Heat pumps for district heating

In order to realize the high potential for district heating, as well as to move away from fossil fuel use for building heating, large-scale electric heat producers need to be installed (Mathiesen et al., 2019). Heat pumps are a very suitable technology for this, since their heat output is much larger than the required electricity input. Furthermore, they can utilize low-grade heat sources for high grade purposes, as the heat is upgraded in a thermodynamic cycle. Heat pumps have been used for district heating in Sweden since the 1980's, to utilize excess electricity from nuclear power plants (David et al., 2013; Werner, 2017b). For the integration of large shares of renewable energy in the future electricity mix, heat pump DH systems could play a similar role. To achieve this, they are to be operated flexibly and in combination with (seasonal) thermal energy storage, to improve the reliability of the heat source as well as the renewable electricity resources like wind and solar power (Lund et al., 2014; Mathiesen et al., 2019).

The functioning of a heat pump depends on three main factors: the heat source, the heat requirement and the heat pump technology. Each of these factors in turn depend on various parameters. This can be visualized in a technical triangle, as can be seen in figure 4 (Sayegh et al., 2018). In the design phase of a DH system with heat pumps, each of these factors need to be considered, aligned with each other and possibly changed (i.e. by reducing building heat demand, involving additional sources, increasing HP thermal capacity) in order to guarantee sufficient functioning of the heating system.

An important indicator for the performance of a heat pump system is the coefficient of performance (COP), or the seasonal average COP, which is called the seasonal performance factor (SPF). The COP is the ratio between thermal energy output and electrical work input, and depends on the input and output temperatures and the system efficiency as percentage of the maximum Carnot efficiency that can be achieved. This efficiency generally lies between 50-70% (De Kleijn, 2020). The COP is given as follows:

$$COP_{HP} = \eta * \frac{T_{out}}{T_{out} - T_{in}} \tag{1}$$

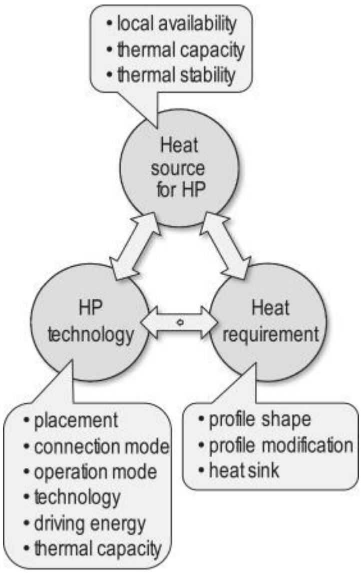


Figure 4: Technical triangle of a heat pump system (from: Sayech et al., 2018)

For the Dutch district-oriented strategy regarding the energy transition, Expertisecentrum Warmte (ECW) and Planbureau voor de Leefomgeving (PBL) developed five scenarios with several sub-scenarios that municipalities can implement to achieve a sustainably heated built environment in 2050 (Hoogervorst et al., 2019). Four of those sub-scenarios involve district heating systems combined with a heat pump, operating with various sources and supply temperatures (S3b-e, see appendix A). Two of these DH + heat pump systems utilize local waste heat. Another system uses an air-source heat pump to deliver water at 50 ºC (which requires an individual booster heat pump as well), and one systems uses energy from surface water to deliver water at 70 ºC. These last two systems both require ATES for seasonal storage of energy. The utilization of waste water as thermal energy source for DH with a heat pump is not a specific scenario within the Startanalyse, but waste water is identified is a potential source of ambient heat (Hoogervorst et al., 2019). The proposed heat pump systems for Benoordenhout correspond with scenario S3d and S3e, respectively. The principles behind this are explained further below.

2.3 TEO

2.3.1 TEO technology

Thermische energie uit oppervlaktewater (TEO) is the Dutch term for thermal energy from surface water, or for a water-source heat pump (WSHP) system. TEO is in fact a combination of several mature technologies, including heat exchangers, distribution pipes and heat pumps. In summer, surface water from a lake, river, canal or sea can reach temperatures of 15-20 ºC, which is warm enough to function as low-temperature heat source for a WSHP system. With heat exchangers, some of this thermal energy can be extracted and stored. The body of water is thereby cooled down by 3-6 ºC (Kruit, Schepers, Roosjen & Boderie, 2018). The storage, in for example ATES, is required to match heating (and cooling) demand year-round, as surface water temperatures vary highly throughout the year, and are mismatched with the peak in domestic heat demand. In winter, the stored heat can be extracted from the ATES source, and upgraded by a central heat pump to temperatures suitable for space heating and domestic hot water use. The hot water is then delivered to the homes through a (new or existing) district heating system (figure 5). A recent study by CE Delft and Deltares estimated that TEO can supply up to 40% of the future energy demand of the Dutch built environment (Kruit, Schepers, Roosjen & Boderie, 2018).

The economic potential of a surface water source indicates whether TEO project would be viable, and is determined by several factors, like extraction capacity, minimum heat demand, distance to consumer and density of heat demand (Kruit, Schepers, Roosjen & Boderie, 2018). The minimum heat demand required for a viable project is generally set at 1 TJ per year. The social potential is the economic potential plus several constraints regarding social and ecological impacts of using the source. The construction and use of a TEO system may have impacts beyond simple investment costs. For example, extracting heat the summer will cool the water body down, which can have positive effects on the heat stress in the neighborhood, but might influence local ecosystems and can interfere with other TEO systems that rely on the same body of water (Stowa, 2017). Therefore, an analysis of the heat potential of the water body needs to be obtained, as well as detailed insight in the heat demand of the surrounding buildings and nearby (planned) projects, so that heat extraction from the water does not cause damage or conflict.

For TEO projects, the typical assumption is that heat can be extracted when the water temperature is over 15 ºC, and the total temperature reduction can be in the range of 3-6 ºC, with a minimum allowable water temperature of 12 ºC. However, there are no legal guidelines on temperature reductions with regard to ecosystems, according to De Lange, Jacobs & Boderie (2017). This same study indicates that the use of TEO in combination with ATES systems are likely to have positive effects on the local ecosystems, as colder water can contain more oxygen and because temperature variability and peak heat stress in summer are reduced. This also creates beneficial circumstances for indigenous fish species, and reduces the risk of harmful cyanobacteria (Dutch: blauwalg).

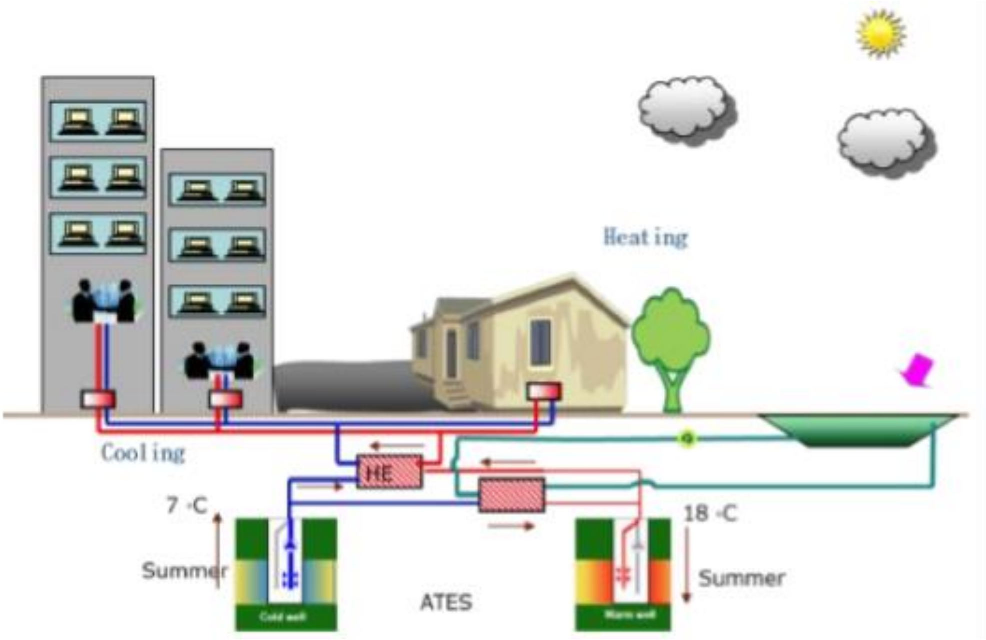


Figure 5: TEO + ATES district heating and cooling (De Lange, Jacobs & Boderie, 2017)

2.3.2 TEO state-of-the-art

The first applications of TEO in the Netherlands have been running for over 30 years, but only recently has it been identified as a promising technology to replace natural gas in the built environment. A few dozen applications are currently in use, mainly for large office or storage buildings (Stowa, 2018). In the last years, there were multiple TEO projects realized for heat supply to neighborhoods. These projects can serve as state-of-the-art examples of TEO technology applications, to provide insight in the implementation and costs of these systems.

For the neighborhood Hoog Dalem in Gorinchem, 230 houses were equipped with a low-temperature heating system and individual heat pump. The houses receive water at around 12 ºC from the ATES system, which is balanced in summer by extracting heat from the nearby canals. An ecological study was performed to assess the impact of the TEO system on the water quality and ecosystem, and no negative impacts were found (Deltares, 2018). It was found that the cooling of the water at a specific point creates a slight flow in the normally stagnant waters, as well as a temperature gradient. At a distance of 1.5 km from the heat exchanger, the water temperature was normalized due to heat exchange with the atmosphere.

For the neighborhood Genderdal, Eindhoven, a TEO + ATES system is designed for 228 homes, mostly built in in 1950's. In summer, warm water is extracted from a drainage channel nearby at 19 ºC, and stored in an ATES well. In winter, the heat is extracted and upgraded by a central heat pump to temperatures high enough to heat the older homes. The CAPEX of the total system are around €2.1 mln, and the OPEX are €85,000 annually. The system will save 2000 GJ primary energy per year, and has a payback time of 11 years (IF Technology, 2018).

2.4 TEA

2.4.1 TEA technology

Thermal energy can also be recovered from the wastewater flowing through large sewer pipes. The Dutch term for term is *thermische energie uit afvalwater* (TEA), or *riothermie*. Wastewater from for example showering, cooking or washing appliances still has a temperature between 8 ºC in winter and 23 ºC in summer when it reaches the sewer system, which would normally be lost to the ground or at the point of discharge. This heat can be extracted by a heat exchanger either in a sewer pipe or at the waste water treatment plant (WWTP). It can then be used as a heat source for a large heat pump system (Culha et al., 2015; Van Weeren et al., 2018). Moreover, wastewater volumes and temperature are relatively high even in winter, so that interseasonal energy storage is not always required (Kleiwegt & De Coo, 2018). However, ATES can be beneficial by reducing fluctuations and increasing heat pump COP in the winter.

Just as with TEO projects, the economic potential of a TEA project is mainly determined by the extraction potential of the wastewater source, the size of the heat demand and the source-user distance (Van Weeren et al., 2018; Kayo et al., 2018). For the social potential, it needs to be considered that there is a limit to the amount of heat that can be extracted. For example, processes for waste water treatment are less efficient at lower temperatures, so a lowering of the waste water temperature during cold periods is not preferred. Heat extraction should therefore take place at sufficient distance from a treatment plant so that temperature differences with the ground are leveled out, or at the outflow pipes of the treatment plant (Van Weeren et al., 2018). A limited temperature difference (ΔT) of 2 degrees is allowed for winter periods and a ΔT of 4 degrees in summer. However, for large volume flows, the heat exchanger will often not reach these temperature differences.

The extraction potential of a wastewater source depends on the volume flow rate (Q) and the temperature lowering by heat extraction (ΔT). It is given by the following formula, with c_p and ρ_w as constants for the heat capacity and density of water, respectively:

$$P_{potential} = Q * c_p * \rho_w * \Delta T \quad (2)$$

As the flow speeds in main sewer pipes are generally high and the temperature differences between mediums are relatively small, long heat exchangers of up to 200 meters are required to extract the heat (see figure 6). This shape causes that a large ground surface (often paved) needs to be opened for installation. The costs of the heat exchanger installation can be reduced when the installation coincides with the natural moment of replacement of old sewer pipes (Kleiwegt & De Coo, 2018).

The actual design of a TEA system depends on various local circumstances, like the type of sewer pipe, diameter, filling degree, soil type, groundwater level and pressurization of the pipe

(Simon Bos, personal communication). Moreover, the applied technology will determine for a large part the actual heat extraction and system costs. For example, the choice of working fluid of the heat exchanger and the heat pump determines the ΔT that can be achieved for a certain heat exchanger length (Simon Bos, personal communication).

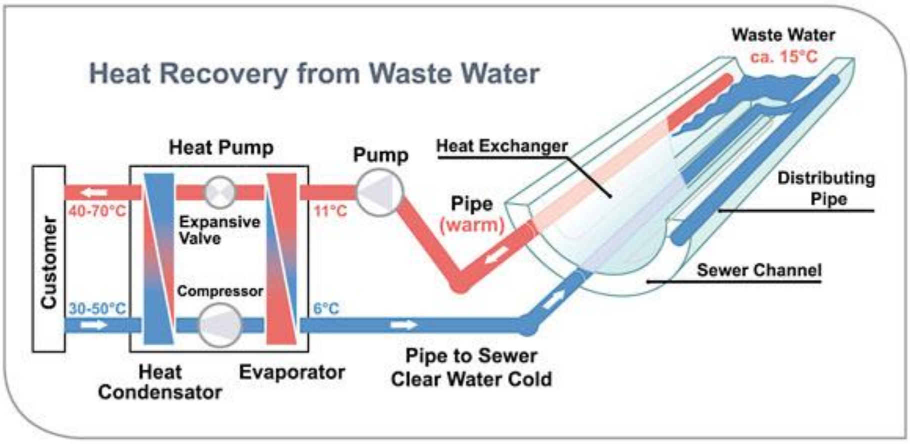


Figure 6: Principle of heat recovery from wastewater

2.4.2 TEA state-of-the-art

TEA, or wastewater source heat pumps (WWSHP) for the term used in international literature, had around 500 applications worldwide in 2014, but its number is increasing rapidly in recent years (Hepbasli et al., 2014). Some relevant projects are outlined below.

Sweden has several large waste water source heat pumps, situated at main treatment plants. In Hammarby, a system of 7 HPs of 225 MWth total is in place. With a COP of 3.5 and 5500 load hours per year, it produces 1.24 TWh of heat annually. In Gothenburg, four heat pumps totaling 160 MWth have been in use since 1985 to deliver hot water to the cities district heating network (Petersen, 2017). The heat pumps heat water to 75-85 ºC, achieving a COP of around 3. Because the pumps are highly flexible, they serve as peak load heat source. In Sandvika, Norway, a similar system of 23 MW is in place to provide heat to the local district heating system, and to defrost sidewalks (Petersen, 2017).

In Budapest, Hungary, three large WWSHPs are in use, to provide heat to a cultural centre, an office and a military hospital. The heat pump for the hospital can provide 3.8 MW of heating and 3.3 MW of cooling. 11,000 m^3 of waste water with a temperature between 10-20 ºC flows by daily, and the heat pumps delivers heat at 32 ºC. The system reaches a COP between 6.5 and 7.1 (Celsius, 2020).

In the Netherlands, TEA has been indicated as an important resource in the energy transition, with the potential to provide around 4% of the Dutch heat demand from the built environment (Kruit et al., 2018). Several projects have been completed or are under development (Van Weeren et al., 2018). In Utrecht, a large TEA system is being developed to extract heat from the wastewater treatment plant in the district of Overvecht. The heat from the waste water effluent at 12-20 ºC will be upgraded to 75 ºC by a heat pump and fed into the existing local district heating network. The heat pump capacity will be 25 MWth, with a possible peak buffer of 15 MWth. Once the system is operative, 400,000 GJ/year will be generated by the TEA system, sufficient for 10,000 households (Van Weeren et al., 2018).

Tauw and Syntraal recently developed several smaller WWSHP systems, that extract heat directly from sewer pipes (Syntraal, 2018). In Urk, a communal swimming pool is heated by a 180 kWth heat pump, which extracts heat from the sewer system via a 120 kW heat exchanger. The HEX is laid as a bypass to the existing sewer pipe, so that disturbance of the wastewater flow during construction is limited and maintenance is easier. Excess heat in summer is stored in an ATES system to be used in winter. The system saves about 165.000 m^3 gas and 310 tons of CO_2 per year (Van Weeren et al., 2018). Similar systems have been installed for pools in Wezep, Raalte and Groningen, and for a school in IJmuiden (Tauw, 2018; Van Weeren et al., 2018).

2.5 ATES

Aquifer thermal energy storage (ATES) is the storage of low to medium temperature (mostly <25 ºC) heat in water bearing layers underground, at a depth of 30-250 meters (RVO, 2017; SIKB, 2014). In these layers, temperature is relatively high and constant throughout the year, so that heat that is injected in the summer can be extracted for heating purposes in the winter. Cold water can be used for cooling buildings in summer, which balances the ATES source. To be able to extract and inject sufficient volumes of water, the soil needs to have a high permeability, that allows for better flow of water through the soil. ATES can be done through a mono-well (vertical separation of hot and cold source) or through a doublet (horizontal separation of hot and cold wells). Mono-wells have lower investment costs, but require thicker aquifer layers (Fleuchaus et al., 2018). In the Netherlands, it is mandatory to maintain a steady energy balance of the ground, so that no more heat is extracted than can be regenerated by cooling of buildings. If the heat load of the ATES source is larger than the cooling demand, additional heat sources, like surface -or wastewater need to be found to restore the balance (see Sections 3.3.1 and 3.3.2) (RVO, 2017).

In Dutch, the common term to describe ATES technology is *warmte-koudeopslag* (WKO), although WKO is al so used to describe shallow ground source heat pumps. The Netherlands can be considered world leaders in the deployment of ATES systems, as around 85% of ATES installations worldwide can be found in the Netherlands, with over 2800 systems in use (Fleuchaus et al., 2018). These are currently mainly used for the seasonal storage of heat for large public buildings like hospitals and universities, but underground thermal energy storage is also part of several strategies to release residential buildings from natural gas, and are used in combination with district heating systems (Van de Weerdhof, 2005).

Whether ATES can be applied, depends on several local circumstances. Most importantly, the subsurface conditions needs to be suitable, which depends on the presence of permeable aquifer layers at reasonable depth, between 30 to 250 meters below ground surface. The aquifer depth, permeability and thickness are the most important factors to consider in the design of ATES systems (Pluymaekers et al., 2012). These characteristics determine for a large part the capital and operational costs of the well, and also determine the ground surface area required for a certain heat demand. Deeper layers will have higher drilling and pumping costs. Layers with lower permeability will possibly require a larger number of wells, and thus higher capital costs and a larger surface area (Van de Weerdhof, 2005). For most parts of the Netherlands, four main aquifer layers can be discerned, separated by less permeable layers (aquitards), according to Pastoors (1992). Aquifer layers consist mostly of sand, and coarse sand with larger grains is more permeable than finer sand. The separating layers consist of clay (Pastoors, 1992; TNO-GDN, 2020). The exact depth and thickness of these layers differ per location. Detailed models of the entire subsurface of the Netherlands based on drilling samples, that can provide insight in the depth, thickness and permeability of these aquifer layers, are created by TNO-GDN and made available online by DINO (TNO-GDN, 2020). Besides geohydrological constraints, the application of ATES is bound by regulatory barriers. The use of ATES can have effect on the quality and level of the groundwater, which can interfere with other uses of that water. For this reason, ATES cannot take place in close proximity to vulnerable (aquatic) ecosystems or near areas where groundwater is extracted to produce drinking water. In urban areas, ATES may not take place in the uppermost aquifer layer, to avoid interaction with underground buildings and infrastructure (IF Technology, 2019). Moreover, nearby ATES systems can interfere with each other. It is therefore important to consider the *thermal radius* of the wells in the design phase. This is the region of thermal influence around a well. Archeologic sites can also form an obstacle for ATES implementation. A general overview of the regulated areas for ATES in the Netherlands is provided in the ATES tool created by RVO (RVO, 2020c).

2.6 Geothermal Energy

2.6.1 Geothermal energy for DH

Geothermal energy is thermal energy that originates from nuclear reactions in the core of the Earth. It can be extracted from deeper layers in the Earth's crust (0.5-6 km), by injecting cold water under high pressure into permeable, water bearing layers of rock, and extracting hot water from a well nearby. These two wells are called a *doublet*. The techniques for ATES and geothermal energy utilization are in fact very similar, and rely on the same hydrological principles for aquifer layers (Pluymaekers et al., 2012). At extraction temperatures above 120 ºC, geothermal energy can be used to produce electricity, or directly used as input for high-temperature district heating system (TNO, 2020a). Sources at lower temperatures, also known as low-enthalpy geothermal aquifers, can be used for medium-temperature DH purposes. Geothermal DH can only be applied where a permeable layer of sufficient thickness is present at a depth that provides a suitable extraction temperature. In the Netherlands, the temperature gradient is 31 ºC/km on average (TNO, 2020a), meaning that an aquifer depth of around 2 kilometers is required to reach extraction temperatures of around 70 ºC. The source temperature is constant throughout the year and fairly constant throughout its lifetime, provided that the injection and extraction well have sufficient distance between them. However, that distance should not be too large because that would require larger, more expensive pumps. The brine that is pumped up from the wells cannot be used directly for heating purposed, as it often contains large concentrations of minerals and heavy metals. Therefore, heat exchangers are used to transfer the heat to a cleaner working fluid (TNO, 2020a). The brine often contains natural gas as well, that needs to be separated. This gas can be combusted to increase the heat output.

The development of a geothermal energy system is a complex, lengthy and costly process, and will take several years of study, preparation, (test)drilling and installation (Agemar, Weber & Schulz, 2014). This, together with the high costs for drilling, lead to very high investment costs and long payback periods of sometimes more than 30 years (Thorsteinsson & Tester, 2010). Geothermal energy can thus only be feasibly deployed for district heating in areas where the heat demand is large, dense and lasting long enough to cover these costs (European Geothermal Energy Counsil [EGEC], 2014). The heat potential of a geothermal well can be increased by optimizing the heat transfer in the district heating system, so that the injection temperature is lowered. Lowering the injection temperature from 40 °C to 30 °C drastically improves the exergetic performance of the well. This can be achieved by applying a heat pump to extract heat from the return flow of the DH system, or by *cascading* the return flow. With cascading, the return flow of buildings with a demand for high temperature (70 °C) serves as inflow for buildings with a lower temperature demand (40°). Thorough scenario analysis, covering geological context study, economic and energetic conditions and regulatory parameters, is therefore essential to develop a feasible project (Daniilidis, Alpsoy & Herder, 2017).

2.6.2 Geothermal DH: State-of-the-art

Geothermal district heating is applied in at least 28 countries, with a total installed capacity of over 7.6 GW. China, Turkey, France, Germany and Iceland are considered world leaders. Especially Turkey and Iceland have favorable geologic conditions due to high volcanic activity, that provide high enthalpy sources at low depth (Lund & Boyd, 2016; EGEC, 2014). One of the largest uses of geothermal energy for district heating systems is found the Paris Basin in Northern France, where heat is acquired from the Dogger aquifer at around 1.5-2 km depth. Since 1970, at least 55 doublets have been constructed, and 29 doublets are still being used to provide district heating to 150,000 households, most of those supply heat above 65 ºC (Lopez et al., 2010). None of the sources have yet shown signs of thermal decline, despite being in use for almost 40 years. In Germany, the city of Munich has drastically increased its geothermal energy production since 2004, to over 250 MWth from 40 doublets. The city is striving to have a city-wide district heating network supplied 100% by geothermal energy by 2040 (Farquharson, Schubert & Steiner, 2016). For this, 400 MWth additional capacity will need to be realized. Recent studies of geothermal district heating in Poland have shown that geothermal district heating is competitive with natural gas or biomass based district heating (Huculak, Jarczewski & Dej, 2015). However, finding private investors for such project was found to be difficult, due to high initial investment and risk and slow rates of return.

In the Netherlands, most of the around 20 geothermal energy systems are used to heat large greenhouse horticulture farms (Platform Geothermie, 2017). No residential district heating systems powered by geothermal energy are currently operative in the Netherlands, but there is a doublet constructed at the Leyweg in The Hague, which is scheduled to be deployed for residential DH in 2020. This doublet was already constructed in 2010, but many partners withdrew from the project during the economic crisis in 2012, and the operation was stalled. However, the wells are still functional and are currently prepared to become operative (HAL, 2020). The wells reach 2.3 km deep, and will supply about 7 MWth at 76 ºC to heat around 4000 houses and several shops and offices. Besides the Leyweg doublet, the municipality of The Hague is planning to expand existing residential district heating systems with three new geothermal sources, for instance to heat several large governmental offices around the central train station (Rijksvastgoedbedrijf, 2018). Some other Dutch cities in promising regions are looking into geothermal DH as well. Daniilidis, Alpsoy & Herber (2017) performed an analysis of a potential geothermal DH system for 10000 homes in the city of Groningen, taking in consideration the large economic and technical uncertainties surrounding the development of geothermal wells. Figure 7 provides an overview of existing Dutch geothermal projects (TNO, 2020a).

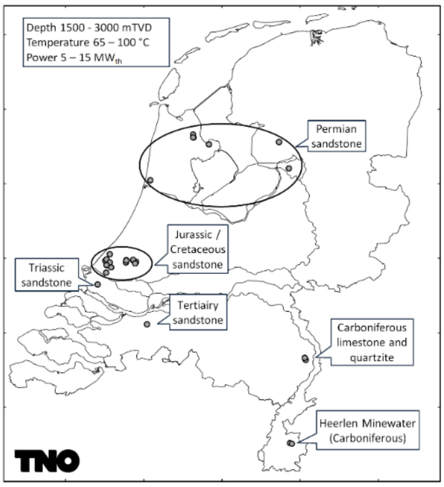


Figure 7: Location and aquifer age of current Dutch geothermal projects (TNO, 2020)

3. Case study – Benoordenhout, The Hague

In this chapter, information is provided regarding the characteristics of the studied district of Benoordenhout in The Hague. An overview is given of the size, building stock, demographic composition and energy demand of the district. Furthermore, the existing energy infrastructure is covered, and placed into context of the larger regional energy system.

3.1 Building stock

Figure 8a and b show the years of construction of all buildings in Benoordenhout. As can be seen, the oldest buildings, built before 1900, are in the southern corner. In the 1920's, the district expanded rapidly north(west) and east. In 1915, the headquarters of BPM, which is now oil company Shell, was built in the west of Benoordenhout, and was expanded in 1928. It is identifiable as the largest building in the district. After World War II, many new homes were needed, and the district expanded further north and east, forming a U-shape around the park of *Landgoed Clingendael.* In 1960, the headquarters of ANWB was built at the southern corner of this park. The newest buildings can be found the neighborhood Duinzigt, in the north of Benoordenhout. Table 1 provides statistics about the building stock of the district. Based on the construction year and type of building, a generic energy label can be assigned to each of the buildings, according to the conversion model for the *Startanalyse* by PBL (Hoogervorst et al., 2019, pp. 38). Due to their age, most buildings in Benoordenhout have an energy label G or F, if they have not yet been retrofitted with measures like floor-, roof- or wall insulation or double (HR++) windows. Information on updated energy labels is available, but only for individual addresses, not on a neighborhood level. Buildings with energy label D-G need a heating supply temperature of at least 70 ºC to reach a sufficient comfort level (DWA, 2019).

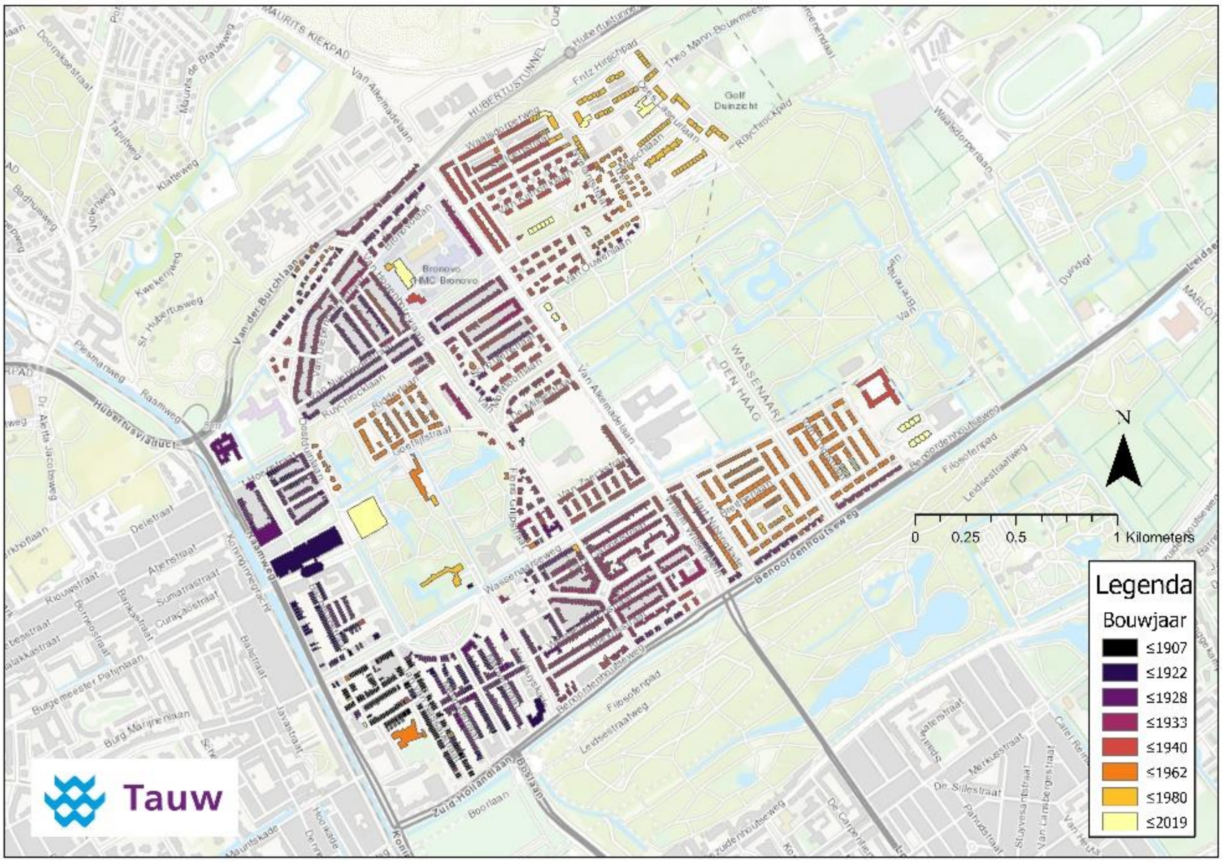


Figure 8a) Map showing building age Benoordenhout (BAG, 2019)

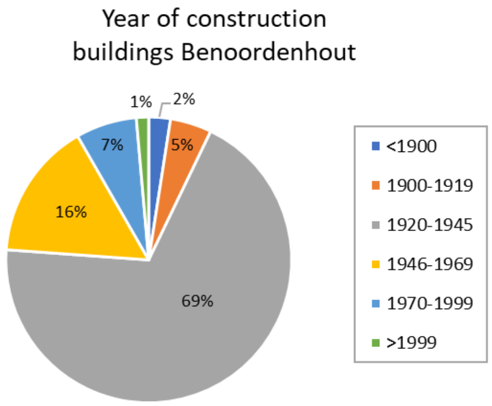


Figure 8b) Year of construction buildings Benoordenhout (BAG, 2019)

Table 1: Key statistics Benoordenhout (CBS, 2020)

Area	274 ha, of which 73 ha parks
Population	13,615
Households	7393
Percentage owner-occupied / rental houses	67 / 32
Average value owner-occupied house	€503,000
Percentage single-family / multi-family houses	29 / 71

Houses can roughly be divided into 5 types: Attached (corner or middle house), semi-detached, detached or apartment. The energy use for space heating is generally different for each of those types, caused by differences in for example surface area, wall area, presence and size of a roof and number of outer walls. To model the energy demand of a neighborhood, it is therefore important to now not only the total amount of houses, but also the number of houses for each type. Using ArcGIS and the neighborhood data from CBS, the number of houses per type in the district of Benoordenhout have been mapped. The numbers are presented in table 2. For these types of houses, ECN and Ecofys made simulations on the annual heat demand, based on insulation characteristics (Menkveld et al., 2015). These heat demand estimations for low-insulated buildings are also provided in table 2.

Table 2: Number of houses in Benoordenhout per type and related energy use

House type	Number of buildings	Heat demand per building (GJ/year)
Attached house (corner)	336	67.5
Attached house (middle)	1651	58.0
Semi-detached house	85	71.0
Detached house	70	98.2
Apartment	5249	42.8
Total	**7391**	**355,980**

3.2 Current energy situation

The dwellings in Benoordenhout are all heated by natural gas boilers, with exception of the very few that might have taken drastic insulation measures and installed a heat pump. A large part of the natural gas pipe infrastructure in the district is currently older than 30 years, and roughly a quarter is due to be replaced in the coming years, according to open data from grid operator Stedin (Stedin, 2020a; RVO, 202b). As the gas network has reached its end of life and new investments and construction periods are due soon, the potential implementation of a district heating network instead of a new gas grid becomes more attractive.

None of the residential buildings in Benoordenhout are currently connected to a district heating network, but there is a district heating network operative in the city center of The Hague, that might be expanded to include parts of Benoordenhout. The location of the existing DH system can be seen in figure 9. In the *Green CityDeal Energierijk Den Haag*, the municipality of The Hague and the national government formulated plans to greatly expand the cities district heating network (Motion2040, 2018). The DH network is currently supplied by the gas-fired Uniper Centrale at the Constant Rebecqueplein, that has a capacity of 100 MWe and coproduces around 1.4 PJ of heat annually. The supply temperature lies around 120 °C, which is much higher than required during most parts of the year. The system currently serves around 17,000 households. New heat sources to be added are the nearly completed HAL geothermal doublet and at least two other new geothermal sources (Gemeente Den Haag, 2014). Furthermore, the integration sources of TEO and TEA are investigated. If the network is to be expanded with other heat sources, the CHP plant output can be lowered, and it could function as back-up source for the coldest days. The DH system of The Hague is also planned to be included in the aforementioned 'Heat Roundabout' of Zuid-Holland (Provincie Zuid-Holland, n.d.). CE Delft recently published a study into the deployment of hybrid district heating networks throughout The Hague (Schilling et al., 2019). These networks would be partly supplied by renewable sources, like geothermal energy, or energy from wastewater or surface water.

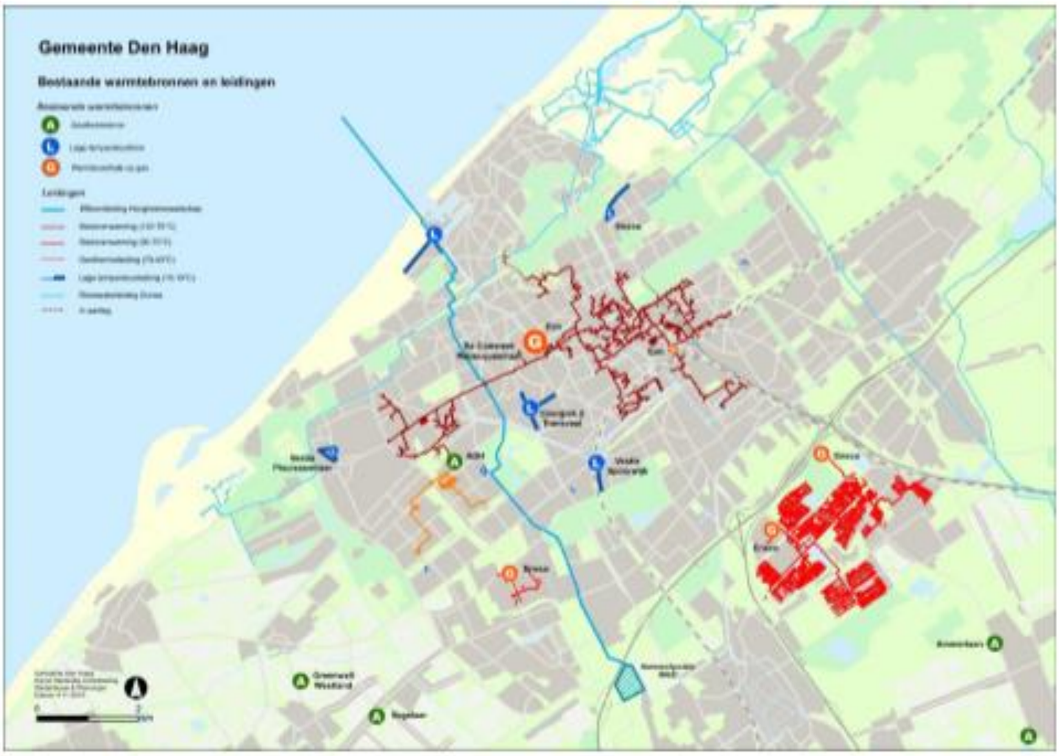


Figure 9: Existing district heating networks in The Hague (Gemeente Den Haag, 2014)

4. Methodology

In this chapter, the methods used in each step of the research process to address the research questions are explained. First, an overview is provided of the research process itself, and the data sources that are used to obtain the required information. Then, the methods used to model the heat demand of the buildings in Benoordenhout in 2030 are described, as well as the reference scenario. Thereafter, the methods for district heating system modelling are described. The subsequent sections explain how the heat potentials of the three heat sources are estimated, and how the functioning and costs of the related technologies are modeled. In the last sections of this chapter, the main inputs and assumptions for the energy model are discussed, the performance indicators for the heat scenarios are described and how the results of these indicators are tested in the sensitivity analysis.

4.1 Research process and data collection

The process of this research consists of several steps, which are presented in the diagram of figure 10 below. Each step will lead to an answer on one of the research sub questions, and finally on the main research questions.

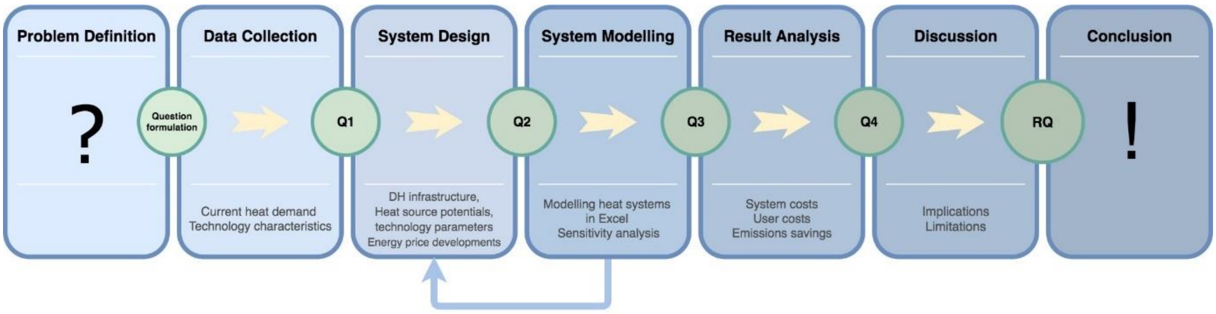


Figure 10: Research process

In each phase of the research, different kinds of data are needed to provide an answer to the research questions. Table 3 provides an overview of the required data and its potential sources per research question. The data type can be either qualitative (descriptive) or quantitative (numerical).

Table 3: Data collection overview

	Required data	Data type	Data source
Question 1	Building data Benoordenhout (year built, type, number)	Qualitative, quantitative	QGIS model with BAG* data
	Heat demand of buildings	Quantitative	Ecofys RVO Energiebesparingsverkenner
	Minimum supply temperature	Quantitative	Technical studies
Question 2	Potential TEO, TEA, ATES (maximum extraction, location, lifetime, supply temperature)	Qualitative, quantitative	Stowa ambient heat tool, Syntraal**, TNO subsurface data, literature
	Geothermal deployment potential (temperature, depth, capacity)	Qualitative, quantitative	TNO ThermoGIS, supporting literature

	Technology characteristics	Qualitative, quantitative	Literature, existing project data, Syntraal
	Cost of equipment and installation	Quantitative	Literature, Vesta MAIS, Ecofys, Syntraal
Question 3	Balancing requirements ATES, TEO, TEA	Quantitative	Tauw, Syntraal, literature
Question 4	Price developments gas and electricity	Quantitative	PBL Klimaat -en Energieverkenning, Vesta MAIS, ING
	Developments Dutch electricity mix	Quantitative	PBL Klimaat -en Energieverkenning, Climate Agreement
	GHG emission factors	Quantitative	Climate Agreement

*BAG (Basisadministratie Adressen en Gebouwen) is a register of Kadaster containing specifications like floor surface, year of construction and energy label of all buildings in the Netherlands

**Syntraal is a subsidiary of Tauw, specialised in the technical analysis of projects

A large part of the input parameters and modelling algorithms for this research are obtained from the Vesta MAIS model. Vesta MAIS is an open source modelling tool developed by CE Delft, that can be used to make calculations about the energy use and emissions of the built environment, as well as for new energy measures and scenarios on a regional scale (CE Delft, 2019). In the Netherlands, Vesta is a widely used tool in the energy transition, and is also the underlying calculation model used for the Startanalyse Leidraad by PBL (Hoogervorst et al., 2019; PBL, 2020). For this research, the Vesta model itself is not used, merely some of its calculation methods obtained from the functional design document (CE Delft, 2019). The reason for this is that the Vesta model does not include several calculation methods, like methods for TEA and geothermal well design.

4.2 Future heat demand

4.2.1 Heat demand forecasting

The total heat demand of the buildings in Benoordenhout throughout the year is modelled using a standardized hourly heat demand simulation dataset for various types of houses, such as attached, semidetached, detached and apartment dwellings, created by Ecofys (Menkveld et al., 2015). This data set includes heat demand for space heating and hot tapwater, and identifies three energy classes: low, medium and high insulation level. Considering the fact that most the houses in Benoordenhout currently have low energy labels like F or G, all houses in the district are now to be classified under the low-insulation category. However, the scenario models will start from 2030 onwards. In the ten years up to 2030, it is likely that national policy regarding residential building insulation will become stricter, similar to the label C requirement that is already in place for office buildings and the energy savings obligation for businesses that requires implementation of energy saving measures with a PBP of less than 5 years. In the Climate Agreement, it is indicated that an insulation standard for typical houses will be developed, based on ‘no-regret’ measures. From 2025, it is expected that these standards will become mandatory (Climate Agreement, 2019 p. 20). Moreover, residents are more and more driven to save energy and money by applying building retrofits. For this study, it is therefore assumed that the average energy label of the residential buildings in Benoordenhout will be label D by 2030. According to RVO’s *Energiebesparingsverkenner*, this corresponds to a 25% reduction in energy demand for space heating, and will place the buildings in the medium insulation category of the simulation dataset (RVO, 2020a; Menkveld et al, 2015). This is also in line with the prognosis of the municipality, who expect a 30% reduction in gas use in the coming years (Gemeente Den Haag, 2014). Buildings with this energy label can be heated with a supply temperature of 65-75 ºC.

With data from the BAG register and the software QGIS, the location and number of houses of each type in the district of Benoordenhout are obtained. The simulated demand values per object of a specific type are multiplied with the total number of objects of the corresponding type to obtain the total heat demand of the district throughout a year. This method does yield high peaks in demand, as all houses will have their peaks at the same time. In reality, the peak demands of households would not occur at the exact same time, and therefore a *simultaneity factor* need to be applied to spread and flatten the districts' peak demand. A simultaneity factor of 0.53 as used by Menkveld et al. (2015) is assumed in this study, which is also similar to the factor used in Vesta (CE Delft, 2019). The number of houses that can be supplied by the assessed district heating systems will determined based on the peak capacity of the heat source and the total annual heat capacity, as compared to the peak demand and annual demand of the modelled individual households.

4.2.2 Business-as-usual scenario

To compare the performance of the proposed district heating systems, a realistic reference scenario is required. This scenario should reflect the energy consumption pattern of households, if no external pressures other than the existing and soon to expect regulations occur. In this research, the aforementioned 'no-regret' insulation standard for residential is expected to be enforced in the near future, so that it can be included in the business-as-usual energy policy. The reference scenario, starting in 2030, will thus be based on the energy consumption patterns of residential buildings with energy label D. Because this reference scenario assumes the same insulation values as the district heating scenarios, the costs of building retrofits up to energy label D are not included in the cost modeling of the collective heating systems. The existing and expected energy policy gives no clear indication on best suited heat source alternatives to natural gas for existing older buildings. The business-as-usual scenario will therefore assume that individual NG-fired boilers will remain the dominant heat source for these older buildings. Indicators on the economic and environmental performance of the reference scenario are addressed in section 4.5

4.3 District heating system design

4.3.1 Heat distribution system

As described in section 2.1.2, the costs of a district heating system consist of three main categories: Cost of heat generation, costs of heat distribution and the costs at the consumer-end to enable DH network connection. The costs of heat generation depend on the fixed and variable costs of the specific heat source. For the various proposed sources for district heating, the breakdown of the costs per source are worked out in sections 4.3.2 to 4.3.5. The cost of heat distribution consists of distributing pipelines, district stations (if the DH system serves more than one district), substations with circulation pumps and heat exchangers, and pipelines from street to house. Also included are costs for design and project management of the DH system. Furthermore, reserve peak boilers that might be needed to match spikes in heat demand are included in the distribution costs (CE Delft, 2019).

Heat capacity

The required thermal capacity of the geothermal source and the transport pipelines in the geothermal DH system depend on the peak required capacity, that is calculated using formula 3.

$$P_{Peak} = Q_{BNH} \times SF \times \left(\frac{1}{1-LF}\right) \tag{3}$$

In this formula, Q_{BNH} is the peak demand of all objects in Benoordenhout summed, as calculated by the methods explained in section 4.2.1. The LF is a distribution loss factor, taken for heat losses occurring in the pipes. Distribution losses of 20% for district-wide systems, and 10% for smaller projects are assumed. The SF is the aforementioned *simultaneity factor* of the peak heat demand of users of the district heating system.

Infrastructure cost

The costs of district heating infrastructure depend mainly on the density of the heat demand and the required thermal capacity of the infrastructure. In the research by Menkveld et al. (2015, pp. 88-89), several types of built environment are discerned, based on building density. The cost per kW required capacity have been estimated, based data of existing DH networks. Figure 11 below shows this specific cost per district type. Benoordenhout can be classified as a ‘green-urban’ district, as marked in the figure. The infrastructure costs of district heating are calculated using these specific cost figures, taking into account the determined heat capacity of the heat sources (in sections 4.3.2-4.3.5).

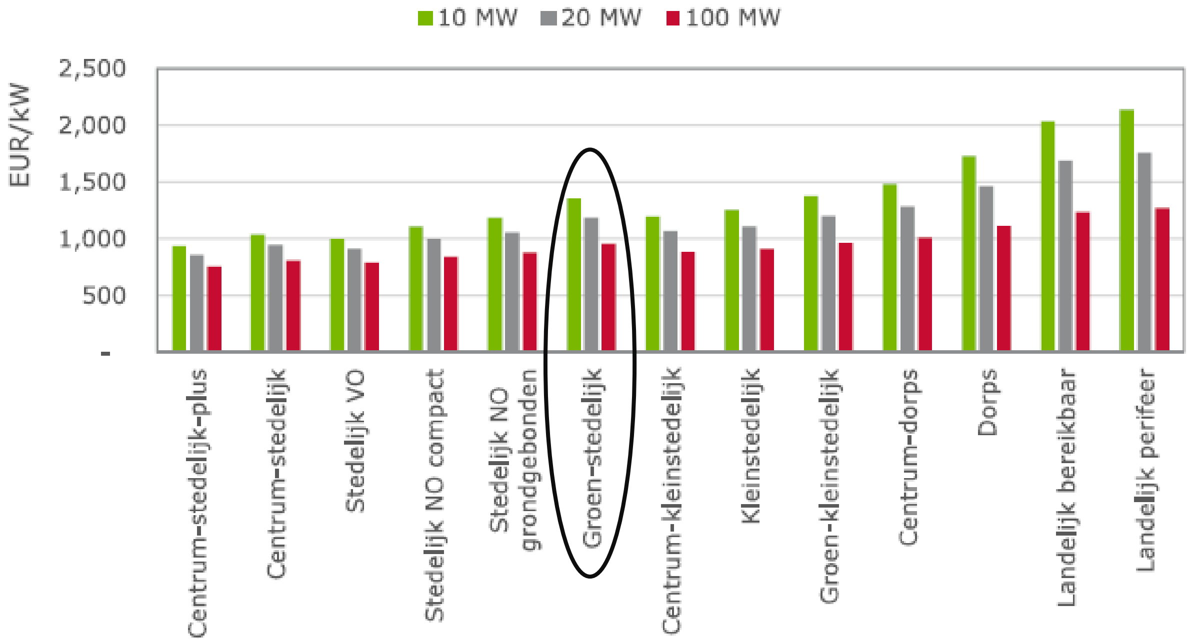


Figure 11: Specific cost of DH infrastructure per building density type and required capacity (Menkveld et al. 2015, p. 89)

Gas grid removal

When a district heating network is installed, most of the existing natural gas infrastructure needs to be removed. The cost of removing one household connection are €792.78 for single-family houses and €169.40 for stacked houses (apartments with formerly collective NG-boiler), according to the prices grid operator Stedin (2020b). Legally, these costs will have to be split 50/50 between grid operator and consumer when the currently pending law proposal is accepted (Stedin, 2020b). When a whole neighborhood is disconnected from the gas grid, most of the main gas pipes will need to be removed as well. The costs of this are estimated by Menkveld et al. (2015, p.87) to be around €270 per connected household, and are assumed to be part of the cost DH network construction. Taking into account the single/multi-family houses ratio in Benoordenhout (table 1), the average cost of gas grid removal are calculated to be €445 per household.

For consumers, disconnection off the gas grid means that they will not have to pay annual transport and connection fees anymore. For this, each household will save €182 annually (Stedin, 2020b).

4.3.2 TEO system design

An online tool was developed by Syntraal, Stowa & Deltares (2020), in which the heat extraction potential of most water bodies in the Netherlands can be found. The potential of a water body depends on how fast it flows (if not stagnant) and on its surface area, depth and solar irradiation. The calculation method is described further in Appendix 2. Using this tool, two locations with the highest potential for TEO near Benoordenhout have been identified. These locations are the Koninginnegracht on the southwest edge of the district, and the Haagse Bosvijver, a large pond in park Haagse Bos at the southeastern edge, as can be seen in figure 12. Both water bodies are assumed to be completely stagnant (before TEO application), and fall within the 0.75-3m depth class.

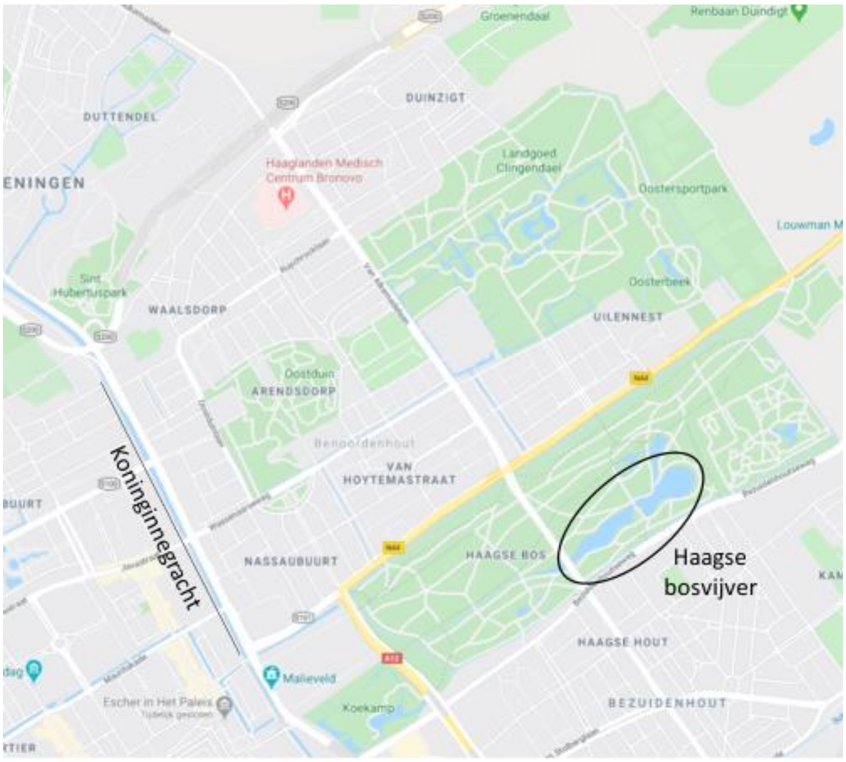


Figure 12: Location of promising TEO water bodies

In the online tool, both water bodies are divided in multiple sections because of crossing bridges, but the water can run freely underneath and the sections can thus be regarded as one large water body. However, the Koninginnegracht is several kilometers long, and it would not be realistic to assume that the energy potential along the entire length of the canal can be obtained with one heat exchanger. Therefore, only the potential of the sections along the district of Benoordenhout are assumed to be obtainable. Using this method, the annual energy potentials of the water bodies are found to be 5139 GJ and 14.424 GJ for the Koninginnegracht and the Haagse Bosvijver, respectively. For both of these locations, a TEO scenario analysis is performed.

To simplify the modelling of the TEO system, it is assumed that the system runs on constant capacity during the summer period when heat is extracted. The system will turn on when the minimum required water temperature of 15 ºC is reached. To find the thermal capacity of the heat exchanger and heat pump, the amount of load hours per year is needed, which thus comes down to the number of hours that the water temperature is above 15 ºC. Typically, it is assumed that the TEO system can run 2000-2500 hours on full capacity (CE Delft, 2019; IF Technology, 2016; Syntraal, Stowa & Deltares, 2018). The lower value of 2000 hours, used in the Vesta model, will be assumed in this research. For an inlet temperature of 15 ºC and an outlet temperature of 70 ºC, the COP of the collective heat pump is calculated to be 3.5. A peak boiler will be used to cover the highest annual peak heat demands, or in case of maintenance or malfunction of the TEO system. The load factor of the boiler is assumed to be 5%. The input values for CAPEX and OPEX of the TEO system components are obtained from Vesta, and are listed in table 4.

Table 4: Input parameters TEO system modelling

Parameter	Unit	Value	Source
Load hours TEO	h/y	2000	Syntraal, Stowa & Deltares (2018)
Load factor peak boiler	%	5	-
Fixed CAPEX TEO heat exchanger	€	95,000	Vesta (CE Delft, 2019)
Variable CAPEX heat exchanger	€/kW	198	Vesta (CE Delft, 2019)
OPEX heat exchanger	%	0	Vesta (CE Delft, 2019)
COP heat pump (15ºC-70ºC)	-	3.5	-
CAPEX heat pump	€/kW	547.5	Vesta (CE Delft, 2019)
OPEX heat pump	% of CAPEX/year	6	Vesta (CE Delft, 2019)

4.3.3 TEA system design

The extraction capacity of heat from the main sewer systems in Benoordenhout are calculated from the flow rate and the temperature decrease from the wastewater in the designated pipes. It is important to consider that not all pipes are suitable for heat extraction, and the placement of heat exchangers should be optimized. The largest sewer pipes, with the highest flow rate, are preferred for TEA deployment, as they have the highest extraction potential. Moreover, these pipes generally have a centralized location in the district, thereby reducing distribution infrastructure length. The sewer system of The Hague is managed by the Water Authority *Hoogheemraadschap van Delfland*. They possess data about the location, properties and flow rate of all main sewer pipes in the region, including those in Benoordenhout (Gemeente Den Haag, 2020). The location of the main sewer pipes is shown in figure 13.

Based on this sewer system data and data and assumptions on groundwater conditions and applied heat exchanger technology, calculations can be made on the extraction potential of the main sewer pipe in Benoordenhout. Such calculations have already been performed by Syntraal. In personal communication with Simon Bos from Syntraal, the extraction potential of the largest sewer pipe in Benoordenhout was found to be 550 kW during the whole year (95% load factor), based on a temperature decrease of the waste water of 1 ºC. However, a temperature decrease of more than 1 degree could potentially be achieved during parts of the year, leading to higher energy yields (Simon Bos, personal communication). In that case, heat exchangers with a larger capacity are needed, and ATES will be required leading to higher costs. The effect of this on the DH system performance will be tested in the sensitivity analysis (see section 4.6).

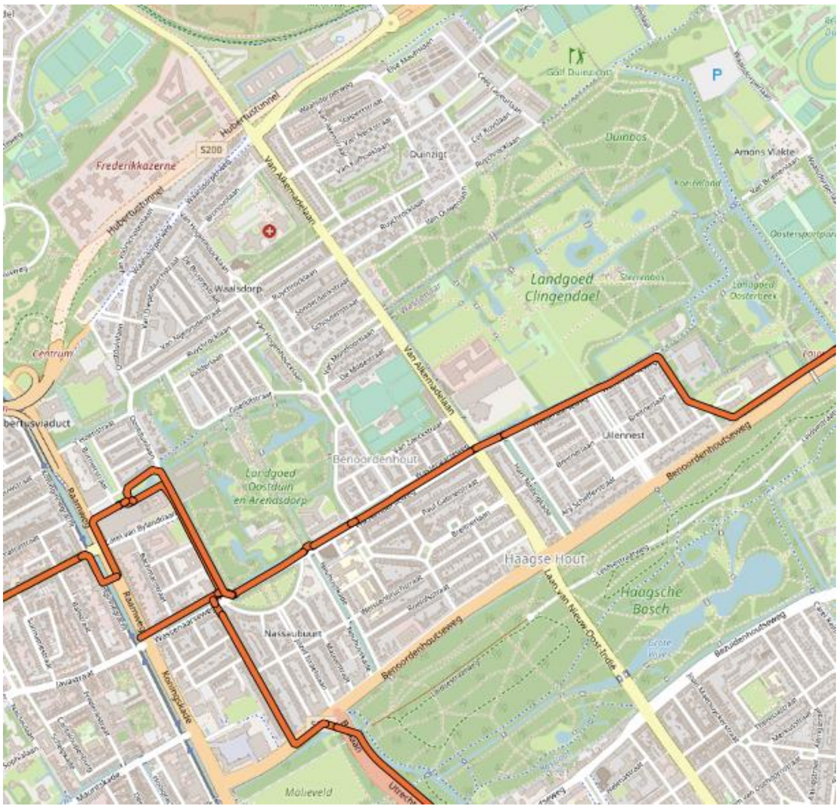


Figure 13: Main sewer pipe below Benoordenhout

Combination with ATES

Most existing TEA systems in the Netherlands operate without the combination with seasonal energy storage, but the energy potential can be significantly increased because waste water temperatures are higher and heat demand is lower in summer (Van Weeren et al., 2018). With this higher energy yield, more houses could be connected to the district heating system. The system is assumed to have a load factor of 95% in case of ATES combination, and a load factor of 50% without ATES. The combination with ATES will provide higher income for the operator, but will have higher initial and operational expenses. Therefore, it is investigated which TEA scenario is economically more attractive. Like with TEO, the TEA systems will be equipped with a natural gas peak boiler, with an assumed load factor of 5%.

Table 5: Input parameters TEA system modelling

Parameter	Unit	Value	Source
CAPEX heat exchanger	€/kW	2000	Van Weeren et al. (2018)
OPEX heat exchanger	€/kW	2	Van Weeren et al. (2018)
COP heat pump	-	3-3.5	-
CAPEX heat pump	€/kW	547.5	Vesta (CE Delft, 2019)
OPEX heat pump	% of CAPEX/year	6	Vesta (CE Delft, 2019)
Load factor TEA with ATES	%	95	-
Load factor TEA without ATES	%	50	-
Load factor peak boiler	%	5	-

4.3.4 ATES design

The functioning and related costs of an ATES system are highly dependent on the characteristics of the subsurface. The depth, thickness and permeability of the underlying aquifers determine how many wells are needed for a certain demand, and what the minimum and maximum flow capacity of the source is. The subsurface of the Netherlands has been modelled by TNO-GDN, based on thousands of drilling samples (TNO-GDN, 2020). The REGIS II v2.2 model herein shows the permeability of the different layers of the subsurface. This model serves as input for a toolbox for ATES modelling created by Tauw, with which the flow rate, size, CAPEX and OPEX and well distance can be calculated.

Subsurface

With the REGIS II v2.2 model, cross section visualizations of the subsurface below Benoordenhout are made, that shows the depth and thickness of the various layers. A cross section of the subsurface of Benoordenhout is shown in figure 14. For each layer the kD (transmissivity) and k_h (horizontal hydraulic conductivity) values are found with this model as well. The k_h value and the kD value (which is the product of k_h and aquifer thickness) determine the rate at which water can flow through the aquifer. The first aquifer layer, at 20-60m depth, may not be used for heat storage in urban areas, as it might interfere with other uses of the shallow subsurface. The second aquifer layer is the yellow/orange at 90-115 meters depth, but this layer is too thin for storage of heat at large volume flows, according to a study into ATES for a neighborhood 2km south of Benoordenhout (IF Technology, 2020). This same study, using TNO REGIS data as well, indicates that the third aquifer layer, the Maassluis Formation between 125-255m depth, is best suited for ATES, mainly due to its thickness. This aquifer does have some lesser permeable clay layers in it, but these are not a barrier for ATES application.

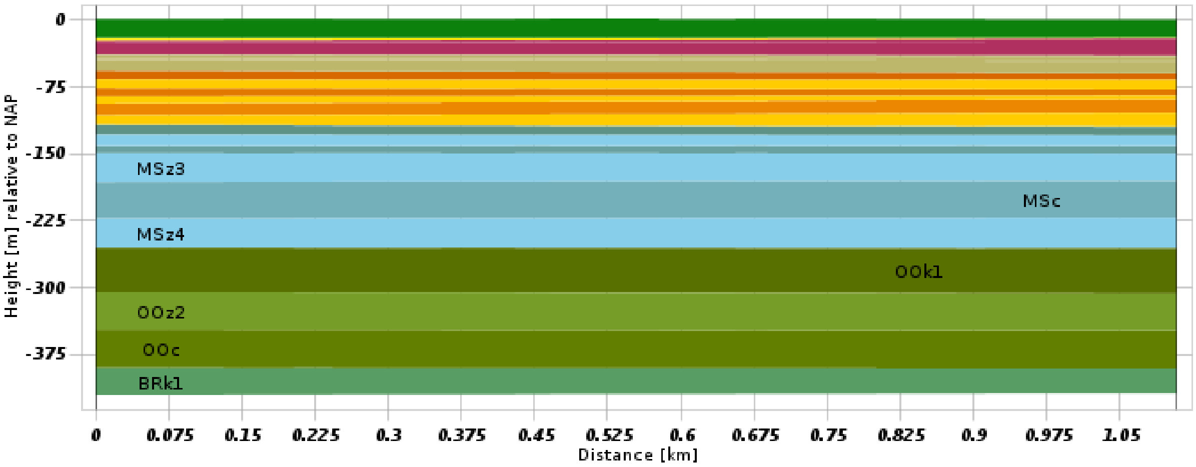


Figure 14: Cross-section of subsurface Benoordenhout down to -450m

Dimensioning of ATES wells

For the ATES design, a doublet system is chosen, as this is the most common type of ATES system in the Netherlands (SIKB, 2014). A doublet system consists of two wells, one hot well and one cold well, that are used both for infiltration and extraction, depending on the season. The flow rate through the wells depends on the amount of heat that needs to be stored (from TEO/TEA for example) and the temperature difference of the extraction and infiltration water that the connected heat pump can reach. The flow rate (in m^3/h) can be expressed in the following formula:

$$Q_{wells} = \frac{P_{source}*3600}{\Delta T*C_w*\rho_w} \tag{4}$$

The rate at which water can enter (extraction) or exit (infiltration) the borehole and filter of the ATES needs to be matched with the required well flow rate, and for this the borehole needs to have the appropriate size. The required borehole size depends on the flow speeds of the aquifer water on the borehole, which are calculated differently for infiltration and extraction. The formulas for calculating the flows speeds are given below.

$$v_{borehole,inf} = 1000 * \left(\frac{k_h}{150}\right)^{0.6} \sqrt{\frac{v_{congestion}}{2MFI*u_{eq}}} \tag{5}$$

In which k_h is again the horizontal hydraulic conductivity, $v_{congestion}$ is the general rate of congestion of the filter (assumed standard value of 0.1 m/y), MFI is the Membrane Filter Index with an assumed standard value of 2 s/l^2 and u_{eq} are the equivalent load hours of the well, which is twice the amount of load hours of the TEO/TEA system.

$$v_{borehole,ext} = \frac{k_h}{12} \tag{6}$$

The speed on the borehole for infiltration is often decisive for the required size of the borehole and filter, as this speed is generally the lowest. The filter size depends on its length and the borehole diameter. The filter length will be as long as the thickness of the aquifer will allow, minus some margin above the lower aquitard. For the Maassluis layer, it is assumed that a filter length of 40 meters is possible. The guideline requirement for the minimum borehole diameter given by the equation:

$$d_{borehole} = \frac{Q_{wells}}{L_{filter}*\pi*v_{borehole}} \tag{7}$$

The practical limit to the borehole diameter would be around 1 meter, according to Rob Ligtenberg from Tauw in personal communication. If this not large enough to accommodate the given flow rate, more doublets are required to spread the heat over a larger area. The number of doublets thus depends on the required flow rate, the maximum achievable filter length and the upper limit of the borehole diameter.

By injecting hot and cold water, the temperature of the aquifer around the well will change over an area depending on the seasonal volume flow, heat capacity of the aquifer and filter length. This area of thermal influence is called the thermal radius. The thermal radius can be calculated with the following function:

$$R_{thermal} = \sqrt{\frac{{}^{1}/_{2} u_{eq}*Q_{well}*c_w}{c_{aq}*\pi*L_{filter}}} \tag{8}$$

In order to keep the hot and cold well from interfering with each other, the spacing between the two wells and between other doublets, needs to be 2-3 times the thermal radius.

The process of storing heat underground requires energy as well, and this energy use determines the efficiency of the system. The ratio between year-round energy delivered (heating and cooling) and energy used by the system is called the *seasonal performance factor* (SPF). The SPF depends on the temperature difference between infiltration and extraction, the pump efficiency and the *head difference* (in Pa). For the pump efficiency and the head, 60% and 425 pascals can be assumed. As a rule of thumb, the SPF of the pump can then be expressed as follows (DWA & IF Technology, 2012; RVO, 2017):

$$SPF_{pump} = \frac{Q_H + Q_C}{E_{in}} = \frac{\rho c_w \eta_{pump}(T_H - T_C)}{\Delta p} \approx 6(T_H - T_C) \tag{9}$$

As both the infiltration and extraction well have a pump with roughly equal energy consumption, the overall ATES SPF can be estimated with:

$$SPF_{ATES} = 3(T_H - T_C) \tag{10}$$

Cost of ATES

The investment costs of an ATES depend mainly on the number of doublets, the borehole diameter, the flow rate and the total borehole depth. The investment costs of a project consist of preliminary studies, licensing and design, test drilling, borehole drilling and casting, pumps and equipment, on site pipelines and technical rooms. The cost estimations for all these components are taken from the ATES model from Tauw. The variable costs of ATES consist of yearly O&M costs, and the pump electricity requirements. The parameters for the ATES design are listed in table 6.

Table 6: Input parameters ATES modelling

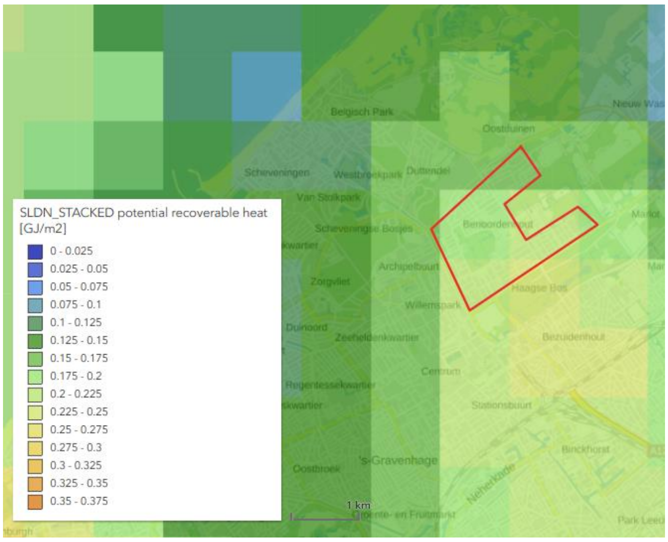
Parameter	Unit	Value	Source
Transmissivity aquifer (kD)	m^2/day	500	TNO-GDN REGIS II v2.2 model
Thickness aquifer (D)	m	50	TNO-GDN REGIS II v2.2 model
horizontal hydraulic conductivity (k_h)	m/day	10	TNO-GDN REGIS II v2.2 model
$v_{congestion}$	m/y	0.1	SIKB (2014)
MFI	s/l^2	2	SIKB (2014)
Filter length	m	40	Assumed, based on D
Yearly load hours (u_{eq})	h	4000	Assumed, based on TEO/TEA load hours
Thermal capacity water	KJ/(kg K)	4.2	
Thermal capacity aquifer	KJ/(kg K)	2.8	Tauw ATES model
Pump efficiency	60%		DWA & IF Technology (2012)
Head difference pump (Δp)	Pa	425	DWA & IF Technology (2012)
Drilling cost (diameter dependent)	€/m/doublet	350-750	Tauw ATES model
Casting cost (diameter dependent)	€/m/doublet	5250-7500	Tauw ATES model
Pumps and equipment (flow rate dependent)	€/doublet	15000-43500	Tauw ATES model
Pipelines on site	€/doublet	10000	Tauw ATES model
Test drilling cost	% of drilling cost	25	Tauw ATES model
Technical rooms	% of equipment	33	Tauw ATES model
Study, design & licensing	% of total CAPEX	15	Tauw ATES model
OPEX ATES	% of total CAPEX	1.5-2	Tauw ATES model

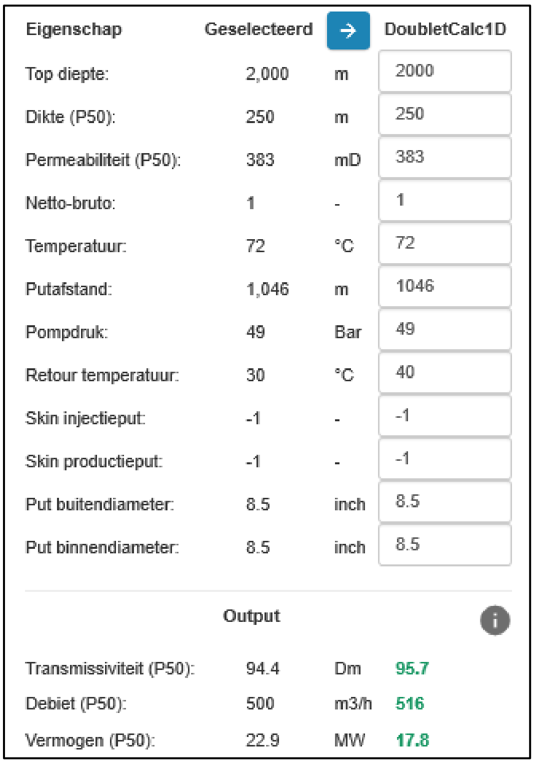
4.3.5 Geothermal system design

For the modelling of the performance of a geothermal well in the area of Benoordenhout, the ThermoGIS software is used. ThermoGIS is open source software created TNO, that can serve as a tool to make preliminary inquiries into the potential of geothermal energy in a specific location. With the viewer tool, insight is given in subsurface layers up to 7 kilometers depth (TNO, 2020b). At the desired certain location, aquifer layers at various depths can be selected for which geophysical properties thickness, temperature, porosity and permeability have been modelled. Together with some input data for the pump and well (return temperature, pump efficiency and pump pressure), the volume flow, maximum thermal capacity and COP are calculated, and the pump size and well distance are optimized. For these calculations ThermoGIS works with the algorithms of the DoubletCalc 1D software, also developed by TNO, based on research by Van Wees et al. (2012) and Vrijlandt et al. (2019).

Location and aquifer selection

The *Malieveld* is a large open field just south of Benoordenhout. This area has been indicated by the municipality and the resident association DSBH as a potential location to deploy a geothermal doublet. Therefore, this location is selected to be analyzed in the ThermoGIS tool. Beneath this location, several aquifers can be found at various depths, each with varying geophysical properties. The Jurassic Delft & Alblasserdam sandstone layer is used by other geothermal projects in the region, as is found to be the aquifer layer with the highest geothermal potential in this location as well. At a *probability of exceedance* of 50% (P50), the geothermal potential is estimated to be 17.8 MW, with an extraction temperature of 72 °C and a flow rate of 502 m^3/h, as can be seen in figure 15b. This capacity is based on an injection temperature of 40 °C.





Eigenschap	Geselecteerd	→	DoubletCalc1D
Top diepte:	2,000	m	2000
Dikte (P50):	250	m	250
Permeabiliteit (P50):	383	mD	383
Netto-bruto:	1	-	1
Temperatuur:	72	°C	72
Putafstand:	1,046	m	1046
Pompdruk:	49	Bar	49
Retour temperatuur:	30	°C	40
Skin injectieput:	-1	-	-1
Skin productieput:	-1	-	-1
Put buitendiameter:	8.5	inch	8.5
Put binnendiameter:	8.5	inch	8.5
Output			
Transmissiviteit (P50):	94.4	Dm	95.7
Debiet (P50):	500	m3/h	516
Vermogen (P50):	22.9	MW	17.8

Figure 15: a) Geothermal potential Delft Sandstone layer b) ThermoGIS output of location Malieveld

Energy and costs modelling

The cost of the well drilling depends on the vertical drilling length (L_V, real depth) of the well in meters, and are calculated with the following formula (Vrijlandt et al., 2019):

$$C_{drilling} = 375000 + 1150 * L_v + 0.3 * {L_v}^2 \tag{11}$$

The L_v of the well is the depth of the top of the aquifer plus half of the aquifer thickness. For a doublet, the calculated well drilling costs are multiplied by 2 (for injection & extraction well). Other costs parameters for geothermal well construction and operation are given in table 7.

Given the plans of the municipality of The Hague and the national government to greatly expand the existing DH system of The Hague with several geothermal heat sources

(Gemeente Den Haag, 2014; Motion2040, 2018), it is reasonable to assume that if a geothermal DH system would be constructed for Benoordenhout, it would be integrated in the existing network. Connecting the geothermal system with the existing DH system of The Hague gives more security of heat supply in case of malfunction and makes sure that the delivery temperature is consistent on the coldest days of the year. Moreover, by connecting to the larger grid, the geothermal well can externally sell surplus heat at times when demand within the district is low, so that the general minimum 68% capacity factor (6000 hours) can always be achieved. At those times, the CHP production for the existing DH system can be reduced.

The pump in the wells of the doublet consumes electricity, and its efficiency can be expressed as the COP ratio between thermal energy pumped up and electricity used. The efficiency of the well pump is estimated at a target COP of 20, in line with Van Wees et al. (2012).

Heat pump scenario

The thermal capacity of the geothermal well can be increased by minimizing the injection temperature. The return temperature of a 70 °C DH system normally lies around 40 °C. If this can be further decreased to 30 °C, the heating potential would be improved by 33%. This additional heat extraction can be achieved by implementing a large heat pump that utilizes the waste heat of the return flow. At these temperatures, an estimated COP of 4.7 can be achieved. The performance of the geothermal DH system will be assessed in two scenarios, one with and one without the implementation of a heat pump to assess the costs and benefits. Table 7 shows the input parameters for the geothermal DH scenarios.

Table 7: Input parameters geothermal doublet modelling

Parameter	Unit	Value	Source
CAPEX fixed	€	3 mln	Vrijlandt et al. (2019)
CAPEX variable	€/kW	300	Vrijlandt et al. (2019)
CAPEX contingency	% of construction	15	Vrijlandt et al. (2019)
OPEX capacity	€/kW	60	Vrijlandt et al. (2019)
OPEX production	€/MWh produced	1.9	Vrijlandt et al. (2019)
Well pump COP	-	20	Van Wees et al. (2012)
Equivalent full load hours	h/y	6000	Vrijlandt et al. (2019)
Heat pump COP	-	4.7	-
Heat pump CAPEX	€/kW	200	Vrijlandt et al. (2019)
Heat pump OPEX	% of CAPEX	5	-

4.4 Energy model input

In this section, the main methods and assumptions and integrated energy trends, that serve as input for the energy model, are discussed.

Trends energy prices and emissions

The prices for electricity and natural gas are expected to be highly dynamic over the period up to 2050, because of changes in energy policy and taxes and developments in energy technology and energy markets. Up to 2030, energy policy is fairly clear, but the development of prices for electricity and natural gas between 2030 and 2050 are highly uncertain.

In the KEV by PBL (2019), the electricity prices for small and large consumers up to 2030 are estimated, based on the current and expected policy of the Dutch government. The electricity price is made up of several components, for each of which the change is estimated (PBL, 2019). In the Vesta model, these price estimations are adopted as well. The development of the electricity price for small and large consumers are provided in Appendix 3. After 2030, it is assumed that the electricity prices will remain at the same level, because the real developments are highly uncertain. Electrification of the energy system is a main goal of the government, and thus are steep electricity price increases not expected (Klimaatakkoord, 2019).

The consumer price of natural gas is expected to increase sharply in the next decade, due to market developments and higher energy taxes. ING estimated that by 2030, the *real* consumer price of natural gas will be 13% higher, not including inflation (ING, 2019). This estimation has been adopted in the energy model. Alternative gas price scenarios will be tested in the sensitivity analysis (see sections 4.6 and 5.7). After 2030, it is uncertain what the price developments of natural gas will be. Therefore, in the energy model the gas price of 2030 will be increased only by inflation up to 2050.

The emission factor for electricity is expected to decrease towards 2050, as the electricity mix will be increasingly fed by renewable sources. The trend in emission factors is obtained from the *Nationale Energieverkenning 2017* (NEV) by ECN (2017), in which projections are made until 2035 based on current and expected policy. In the Climate Accord, the emissions from electricity generation are targeted to be zero (Climate Accord, 2019), so the emission factors from the NEV in 2030 are gradually reduced to 0 over the 2030-2050 period.

Consumer costs of district heating

The maximum consumer cost of district heating is set by Dutch law, in the *Warmtewet* (Heating Act) as stated by the Autoriteit Consument & Markt (ACM, 2020). Herein, the one-off and yearly price of connection to the DH system and the cost of heat per GJ delivered are stated, among others. The maximum price of heat (per GJ) from district heating may not be higher than the average price of heat from natural gas in the previous year (ACM 2020; CBS, 2020). An overview of the maximum prices of heat are provided in Table 8. From the difference between the actual cost of heat for the proposed district heating system and the regulated maximum price of heat, the profits/losses for the supplier and the required subsidies can be calculated.

Table 8: Maximum consumer costs for district heating in 2020 (ACM, 2020)

Type of cost	*Cost (incl. VAT)*	*Cost (excl. VAT)*	*Unit*
Connection fee (one-off)	**4510.73**	**3727.88**	**€**
Fee space heating + DHW	**469.17**	**209.20**	**€/year**
Price of heat delivered	**26.06**	**21.54**	**€/GJ**
Measuring fee	**26.63**	**22.01**	**€/year**
Renting fee delivery set	**126.19**	**104.29**	**€/year**

As discussed in section 2.1.3, the consumer costs for district heating are increasingly debated, due to their current coupling to the (rising) natural gas price. In this research, the default assumption is that the maximum prices for DH will soon be decoupled from the gas price, and be fixed at the current rate. Up to 2030, and onwards to 2050, the maximum price is assumed to only increase in line with inflation.

General assumptions

For the development phase of the district heating systems, a period of 5 years is estimated. The construction of the projects is assumed to start by 2025, so that the systems can be operable by 2030. The construction costs of the district heating systems are assumed to be spread evenly over those 5 years.

It is assumed that all residents of Benoordenhout are willing to connect to a district heating network. In other words, a participation rate of 100% is assumed in all scenarios. In reality, this value is likely lower, depending on the social support for district heating. This is discussed further in chapter 6.

For all projects, no subsidies are assumed in the modelling of the financial indicators. Presently, it is possible to apply for a subsidy for carbon-reducing projects like TEO, TEA and geothermal energy. These subsidies, called the *Stimulation of Sustainable Energy Transition* (SDE++), are disbursed from a budget that is annually assigned by the national government (RVO, 2020d). However, the size of this budget varies highly every year, and it is uncertain whether this subsidy scheme, or anything similar, will be present in 2030. For this reason, subsidy expectations are left out of the equation. From the financial results without subsidy, conclusions are drawn regarding required subsidies in the future.

Table 9 contains the main economic input values for the energy model.

Table 9: Overview of economic model input parameters

Parameter	Value	Unit	Source
Inflation rate	2	%	PBL (2019)
Social discount rate	3	%	PBL (2019)
Discount rate geothermal	7	%	Vrijlandt et al. (2019)
Electricity price large (2030)	0.137	€/kWh	Vesta and PBL (2019)
Electricity price small (2030)	0.263	€/kWh	Vesta and PBL (2019)
Gas price large (2030)	0.406	€/m^3	Vesta and PBL (2019)
Gas price small (2030)	1.06	€/m^3	ING (2019)

4.5 Result Analysis

Resulting from the calculated capacity of the heat sources and ATES systems and the cost of the components of the proposed heat systems, an annual balance of costs and revenues for the system operator can be made for the period 2025-2050. As stated before, the construction of the DH networks will take place in the period 2025-2030, and these five years will thus be characterized by large annual costs and no revenues. From 2030 onwards, the systems will start generating annual revenues as well as operating costs. Furthermore, the systems will use energy from which emissions will occur. To compare the performance of these various technologies in DH systems of different sizes with each other and the reference scenario, several economic indicators will be used.

Net Present Value

To assess the viability and economic attractiveness of a project, all future costs and benefits over the lifetime of the system should be summed, while taking into account the time preference of money of the investor. This latter is expressed in the real discount rate (r) of the project. The real discount rate is the discount rate minus the rate of inflation. The Net Present Value (NPV) gives these weighted costs and benefits in one value, and is calculated according to formula 12:

$$NPV = \sum_{i=0}^{n} \frac{B_i - C_i}{(1+r)^i} \tag{12}$$

The NPV of a project should be positive to be considered economically attractive. In this research, a discount rate of 3% will be used, which is the same as the social discount rate used by PBL in their impact assessment of the Climate Accord (Hekkenberg & Noteboom, 2019). However, for geothermal projects the discount rate is generally higher, as these projects come with high risk. For the geothermal DH scenario, a discount rate of 7% will be used, in line with Van Wees et al. (2012).

For the residents of Benoordenhout, a NPV can also be calculated. Their costs, being the costs of connection to a district heating network, are weighed against the benefits of saved NG related expenses compared to the reference scenario. The consumer NPV will be the same for all DH scenarios, as the connection costs for DH are assumed to be equal in each scenario.

Levelized Cost of Heat

Taking into account all the investments and annual expenses that have to be made to produce a certain amount of heat, a lifetime average price for the delivered heat can be calculated, again by taking into account time preferences. This price is called the Levelized Cost of Heat (LCOH), and is calculated according to formula 13:

$$LCOH = \frac{\sum_{i=0}^{n} \frac{I_i + OM_i + F_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{H_i}{(1+r)^i}} \tag{13}$$

In which:

i = *project running year*
n = *project lifetime*
B = *project benefits*
C = *project costs*
I = *investment costs*
OM = *Operation & Maintenance costs*
F = *fuel costs*
r = *discount rate*
H = *heat output*

Cost of avoided CO$_2$-emissions

For every heat system, an emission factor of the delivered heat can be calculated, which is the amount of CO$_2$ that is released per unit of heat produced. It is calculated by dividing the total amount of CO$_2$ released by the heating system in the operating period (2030-2050) by the total amount of heat produced over the same period:

$$FactorCO2 = \frac{Total\ emissions}{Total\ heat\ produced} \tag{14}$$

The implementation of the district heating systems is expected to decrease the emission factor of heat in comparison to the reference scenario. At the same time, the LCOH will change as well, meaning that a reduction in emission change comes with a certain cost. This cost can be compared between the different scenarios using the *cost of avoided CO$_2$*, with a value in €/ton CO$_2$. It is calculated as follows:

$$Cost\ of\ CO_2\ avoided = \frac{LCOH_{new} - LCOH_{ref}}{FactorCO2_{ref} - FactorCO2_{new}} \tag{15}$$

It should be noted that the resulting value is relative: it is dependent on the emission factor and LCOH of the reference scenario. The cost of CO$_2$ can also be negative, meaning that emissions are saved at lower cost than the reference scenario. The LCOH of the reference scenario depends on the future price of natural gas and on the costs of constructing and operating the natural gas grid. The latter are paid for by the customer through an annual connection fee (in Dutch: 'vastrecht'). Current and expected market and policy trends are expected to raise the price of natural gas, as explained in section 4.4. Table 10 shows the cost components of the reference scenario.

Table 10: Cost components of reference scenario

Component	Value	Unit	Source
Investment NG-boiler	2100	€	Milieucentraal (2020)
Lifetime NG-boiler	20	Years	
Natural gas cost 2030	1.06	€/m³	ING (2019)
Efficiency NG-boiler	95	%	
O&M NG-boiler	50	€/year	
Connection fee (vastrecht) NG grid	181.94	€/year	NIBUD (2020)

Table 11 gives an overview of the economic and environmental indicators.

Table 11: Economic and environmental indicators

Name of indicator	Explanation
Net present value (NPV)	Lifetime discounted costs and benefits summed, expressed as single value
Levelized cost of heat (LCOH)	Discounted lifecycle costs per MWh heat supplied
Cost of CO_2 avoided	Extra costs over emissions saved, compared to reference system
Emission factor of delivered heat	CO_2 emissions per unit heat delivered

4.6 Sensitivity Analysis

The outcome of the result analysis for the three heat systems will depend on the values of the input data. For a significant portion of this data, uncertainty exists around the precise value, as it may be based on estimations, projections, averages, assumptions or older sources. Moreover, values obtained from literature are sometimes inconsistent, or very case-specific. Changes in the actual value of this data might have a considerable effect on the outcome of the models. Therefore, it is important to test what the potential range of outcomes is and to investigate which variables have the largest influence on the outcome of a project. To this end, a sensitivity analysis is carried out on the most important input data for which uncertainty may exist. For each variable, a range of potential values is tested using the *What-if* analysis - data table function in Excel. In Table 12 below, an overview is given on the input parameters and their respective value range for which the sensitivity analysis is carried out.

Table 12: Parameters subject to sensitivity analysis

Parameter	Default value	Value range	Tested for effect on
Price of electricity (2030, large consumer)	0.137 €/kWh	-40% - +40%	NPV, LCOH
Price of natural gas (2030, small consumer)	1.06 €/m³	Low (0.77) Medium (0.92) High (1.06) Very high (1.20)	Cost of CO_2 avoided
Discount rate	3% (TEO, TEA) 7% (Geothermal)	2-7% 3-9%	NPV, LCOH
Inflation rate	2%	1.5-2.5%	NPV, LCOH
Heat pump efficiency	60%	50-70%	Cost of CO_2 avoided
Supply temperature heat pump	345 K (72ºC)	340-360 K	Cost of CO_2 avoided

Simultaneity factor of heat demand	0.53	0.50-0.85	NPV, LCOH
Loss factor district heating	0.10 (TEO, TEA) 0.20 (Geothermal)	0.05-0.25 0.10-0.35	NPV, LCOH
Specific cost DH pipelines	1500 €/kW (TEO, TEA) 1000 €/kW (Geothermal)	1200-1800 800-1300	NPV, LCOH
CAPEX heat technologies	Technology dependent	-66% - +66%	NPV, LCOH
OPEX heat technologies	Technology dependent	-66% - +66%	NPV, LCOH

Furthermore, for the TEA + ATES system, it is tested how the performance of the system would change if it would be possible to cool the waste water flow with 2 degrees during the summer period, instead of 1.

For the price of natural gas in 2030, four different price categories are chosen. It is very unlikely that the gas price in 2030 will be lower than the current price. Therefore, the lowest price category is the current average consumer price, while the *medium* category is the current price plus a 2% annual inflation rate. The *high* price category, being the default value in the energy model, is based on the projected gas price in 2030 based on current and expected policy (ING, 2019). The *very high* category is a scenario in which the government would adopt even stricter methods to divert consumers away from natural gas.

5. Results

In this chapter contains the results of the heat demand and the analyses of the three district heating technologies. These include the potential of connected households, a system cost overview and the scores on the economic and environmental indicators NPV, LCOH and cost of CO_2 avoided. Furthermore, the sensitivity of these results to variations in input parameters is illustrated.

5.1 Heat demand Benoordenhout

Using the simulation dataset from Ecofys (Menkveld et al., 2015) and the information on the building stock in the district, the total annual heat demand of the district, the average heat demand per household and peak demands are calculated. Furthermore, the emissions arising from this heat demand in the reference scenario, and the levelized cost of heat in the reference scenario have been calculated. In table 13, the key heat demand values are listed.

Table 13: Modelled heat demand characteristics and reference LCOH Benoordenhout in 2030

Per household		
Average yearly heat demand	10.72	MWh
Of which hot tap water demand	2.53	MWh
Reference natural gas demand	1180	m^3
Reference CO_2 emissions	2044	kg/year
Peak heat demand average household	14.3	kW
Total district		
Annual heat demand	79223	MWh
Peak heat demand (corrected for simultaneity and heat losses)	70.0	MW
Reference emission factor	0.214	t/MWh
Total reference CO_2 emissions	15105	t/year
Reference LCOH	164.00	€/MWh

The LCOH of heat from natural gas boilers for consumers is calculated to be €164.00 by 2030. This cost consists of the purchase of a new natural gas boiler (once in the period 2030-2050), the cost of natural gas at average simulated gas consumption and 2030 gas prices, and the annual cost of boiler O&M and grid connection fee. The emission factor of heat supplied by a single-building natural gas boiler (at 95% efficiency) comes down to 214 kg CO_2 per MWh.

5.2 District Heating based on TEO and ATES

Based on the extraction capacity of the two potential locations for TEO, the Koninginnegracht and the Haagse Bosvijver, the size of the DH systems was calculated. From the corresponding number of connected households, and with the cost models for TEO, ATES and DH, the economic and environmental performance of the two systems were calculated. Table 14 gives an overview of the results of the TEO based district heating systems.

Table 14: Results of the TEO + ATES district heating system models

TEO location Koninginnegracht		
Annual heat extraction	5139	GJ
HEX capacity	714	kW
Heat pump COP	3.5	-
Heat pump thermal capacity	998	kW

Households connected	168 (2.3%)	
Annual heat supplied (loss corrected)	1797	MWh
Natural gas use peak boiler	323	GJ
CAPEX TEO system	782,883	€
CAPEX ATES system	403,966	€
Number of ATES doublets	2	-
CAPEX DH infrastructure	2,556,380	€
NPV	-2,410,280	€
LCOH	234.64	€/MWh
Total CO_2 emissions avoided 2030-2050	5324	tonnes
Emission factor of heat	0.0513	t/MWh
Cost of CO_2 avoided	432.83	€/tonne
TEO location Haagse Bosvijver		
Annual heat extraction	14424	GJ
HEX capacity	2003	kW
Heat pump COP	3.5	-
Heat pump thermal capacity	2802	kW
Households connected	418 (5.7%)	
Annual heat supplied (loss corrected)		MWh
Natural gas use peak boiler	1009	GJ
CAPEX TEO system	2,025,733	€
CAPEX ATES system	1,041,958	€
Number of ATES doublets	2	-
CAPEX DH infrastructure	6,377,934	€
NPV	-5,443,416	€
LCOH	213.02	€/MWh
Total CO_2 emissions avoided 2030-2050	12881	tonnes
Emission factor of heat	0.0501	t/MWh
Cost of CO_2 avoided	298.27	€/tonne

As can be seen in table 14, the number of household that can be supplied by either TEO location is only a small fraction of the total building stock in Benoordenhout. Given the small annual heat production and resulting revenues, the investments in the heat technologies and infrastructure are not earned back before 2050, and subsidies would be needed to make these TEO projects economically attractive. The cost of heat in both scenarios is substantially larger than that of the reference scenario based on natural gas, which makes the cost of avoided CO_2 very high, even though the emission factor of the TEO systems is much lower than that of natural gas. The necessity of the backup boiler for peak demands makes that the system remains fossil-fuel dependent, unless the gas would come from a green source.

5.3 District Heating based on TEA

An overview of the results of the district heating system based on TEA + ATES is provided in table 15.

Table 15: Results of the TEA with and without ATES district heating system model

Scenario TEA with ATES		
HEX capacity	550-1100	kW
Heat pump COP	3.5	-
Heat pump thermal capacity	2308	kW

Households connected	368 (5.0%)	-
Annual heat supplied (loss corrected)	3946	MWh
Natural gas use peak boiler	1201	GJ
CAPEX TEA system	3.407.739	€
CAPEX ATES system	459.172	€
Number of ATES wells	2	-
CAPEX DH infrastructure	5,457,579	€
NPV	-6,519,742	€
LCOH	248.49	€/MWh
Total CO_2 emissions avoided 2030-2050	13834	tonnes
Emission factor of heat	0.0498	t/MWh
Cost of CO_2 avoided	513.14	€/tonne
Scenario TEA without ATES		
HEX capacity	550	kW
Heat pump COP	3.3	-
Heat pump thermal capacity	785	kW
Households connected	125 (1.7%)	-
Annual heat supplied (loss corrected)	1343	MWh
Natural gas use peak boiler	409	GJ
CAPEX TEA system	1.401.112	€
CAPEX DH infrastructure	1.852.996	€
NPV	-2.055.306	€
LCOH	245.21	€/MWh
Total CO_2 emissions avoided 2030-2050	4805	tonnes
Emission factor of heat	0.0458	t/MWh
Cost of CO_2 avoided	481.39	€/tonne

These results show that the energy potential of wastewater is significant, but by far not large enough to provide heat to the entire district. Combining TEA with an ATES system does increase the potential almost threefold, by allowing the system to run for almost the entire year and at higher average COP. However, the additional costs for the ATES system and the larger DH system give the system a lower NPV. The LCOH of both systems are roughly equal, and significantly higher than the cost of heat in the reference scenario. Both systems will require significant subsidies to be economically viable, which is due to the high investment costs, mostly of the DH infrastructure, that are not earned back by the limited number of connected households. Compared to TEO, TEA achieves higher heat prices, with comparable emission factors. The costs of avoided CO_2 are thus higher.

5.4 Geothermal District Heating

Based on the physical properties of a geothermal doublet at the Malieveld as calculated with ThermoGIS, it was found that at 6000 full load hours, the doublet could produce enough heat to match the annual demand of all households in Benoordenhout. During moments of peak demand, the geothermal capacity is insufficient and additional heat will need to be supplied the by the other heat sources of the existing DH network, currently supplied by the Uniper gas-fired CHP. However, for large parts of the year, the heat capacity of the geothermal grid is larger than the heat demand from Benoordenhout, so that the Malieveld doublet can supply other buildings in The Hague with low-carbon heat. All in all, the geothermal doublet can provide more heat than Benoordenhout uses, but as long as the larger district heating system is supplied by natural gas, Benoordenhout will continue to rely on fossil fuels to meet its' peak heat demand. This is the case in both scenarios, with and without heat pump implementation. An overview of the results of the geothermal energy model is provided in table 16.

Table 16: Results of the geothermal district heating system model

Geothermal district heating network		
Doublet capacity	17.8	MW
Supply temperature	72	°C
Number of households connected in Benoordenhout	7391 (100%)	-
CAPEX geothermal doublet	19,897,875	€
CAPEX DH infrastructure	77,696,077	€
Scenario without heat pump		
Annual heat supplied (loss corrected)	85,440	MWh
NPV	16,364,348	€
LCOH	143.12	€/MWh
Total CO_2 emissions avoided 2030-2050	351,381	tonnes
Emission factor of heat	0.00697	t/MWh
Cost of CO_2 avoided	-100.66	€/tonne
Scenario with heat pump		
Annual heat supplied (loss corrected)	121,027	MWh
CAPEX heat pump	4,059,107	€
NPV	31.768.093	€
LCOH	106.07	€/MWh
Total CO_2 emissions avoided 2030-2050	570,253	tonnes
Emission factor of heat	0.01262	t/MWh
Cost of CO_2 avoided	-286.99	€/tonne

The figures in table 16 show that the potential for geothermal energy to be implemented as sustainable alternative for the existing natural gas boilers is certainly promising. In the scenario without heat pump cascading, enough energy is produced to cover the annual heat demand of Benoordenhout, with a levelized cost of heat lower than for the reference scenario based on natural gas. Over 350 kilotonnes of CO_2 emissions can be avoided between 2030 and 2050, and as the LCOH of heat is expected to be lower than that of natural gas, the cost of avoided CO_2 are *negative*. This means that the produced geothermal heat is both cleaner and cheaper than the reference heat production. The NPV of the project is positive, meaning that no subsidies are needed to make the project economically viable.

In the scenario where a heat pump is implemented at the return flow of the DH system, the heat production is considerably higher, while the additional costs are limited. The LCOH and NPV of the project are thus improved, and are the best of all scenarios. The emission factor of the produced heat is higher than for the no heat pump scenario, because of the larger electricity consumption. However, the total amount of emissions avoided are much greater.

5.5 Result overview

Figure 16 and 17 provide a visual comparison of the levelized costs of heat and the cost of CO_2 avoided for the various scenarios. It is evident that the two geothermal district heating systems are found to perform best. A district heating system based on geothermal energy comes with high initial cost, but is able to provide the entire district with heat and can achieve high NPVs and low LCOHs. Figure 16 shows that only the geothermal scenarios are expected to deliver heat at lower production cost than the reference system with a natural gas boiler. The LCOH of the four TEO and TEA systems are well above the reference LCOH, with the

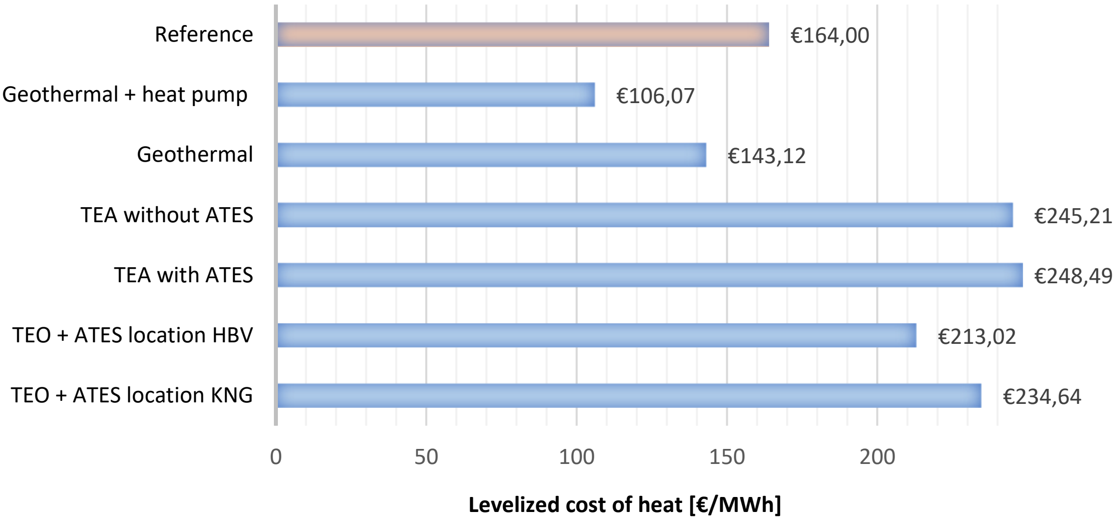


Figure 16: Overview levelized costs of heat for all scenarios

Figure 17 shows the cost per avoided tonne CO_2 for all scenarios. Where the geothermal scenarios can 'earn' money while avoiding emissions, the TEO and TEA scenarios would require heavy subsidies for their efforts of emission reduction. The costs of these scenarios are so high, that the currently existing subsidy scheme would not cover them entirely. To illustrate, a price over 300 €/tonne places a CO_2-reducing technology beyond the lowest priority group for an SDE++ subsidy in the current regulation (RVO, 2020d). This means that at present day, the studied TEO/TEA systems for Benoordenhout would likely not get subsidy, or at least not enough to cover the entire cost.

Figure 17: Overview cost of CO_2 avoided for all scenarios

5.6 Consumer cost of district heating

For consumers, a LCOH and NPV for connection to a district heating system are calculated (Table 17). These are the same for all systems, as the maximum fees for DH from ACM are assumed to hold for all scenarios.

Table 17: NPV and LCOH of district heating for consumer

Indicator	Value	Unit
Net Present Value	-11.978	€
Levelized Cost of Heat	212.03	€/MWh
Reference LCOH	164.00	€/MWh

From these results, it becomes clear that switching to district heating is not financially attractive, even for higher future gas prices. This matter is discussed further in chapter 6.

5.7 Sensitivity Analysis

A sensitivity analysis was performed over the most important input parameters, with value ranges as given in table 12. The most relevant sensitivities of the LCOHs, NPVs and cost of CO_2 avoided are discussed in this section. In Appendix 4, the graphs visualizing the sensitivity of the NPV and LCOH of the different scenarios for the various indicators, are displayed.

In all scenarios, the largest cost factor is the construction of the district heating system. The financial results of the scenarios are thus highly sensitive to changes in the values parameters that influence these costs. These factors are the *specific DH pipeline costs*, the *simultaneity factor* and the *DH loss factor*. In the discussion, further reflection is given on the importance of (the accuracy of) these factors. None of the four TEO and TEA scenarios would be viable if DH infrastructure needs to be constructed and operated specifically for their purpose, as would currently be the case in Benoordenhout. However, if these infrastructure costs could be disregarded, in case of an existing DH network for example, the LCOH and NPV of TEO and TEA projects will likely improve drastically, and a viable business case could be developed. Figure 18a and b illustrate what the LCOH and NPV of the TEO and TEA scenarios would be, if the DH construction costs could be disregarded. As can be seen, the 'pure' costs the heat technology only are significantly lower, and can even be lower than the reference LCOH.

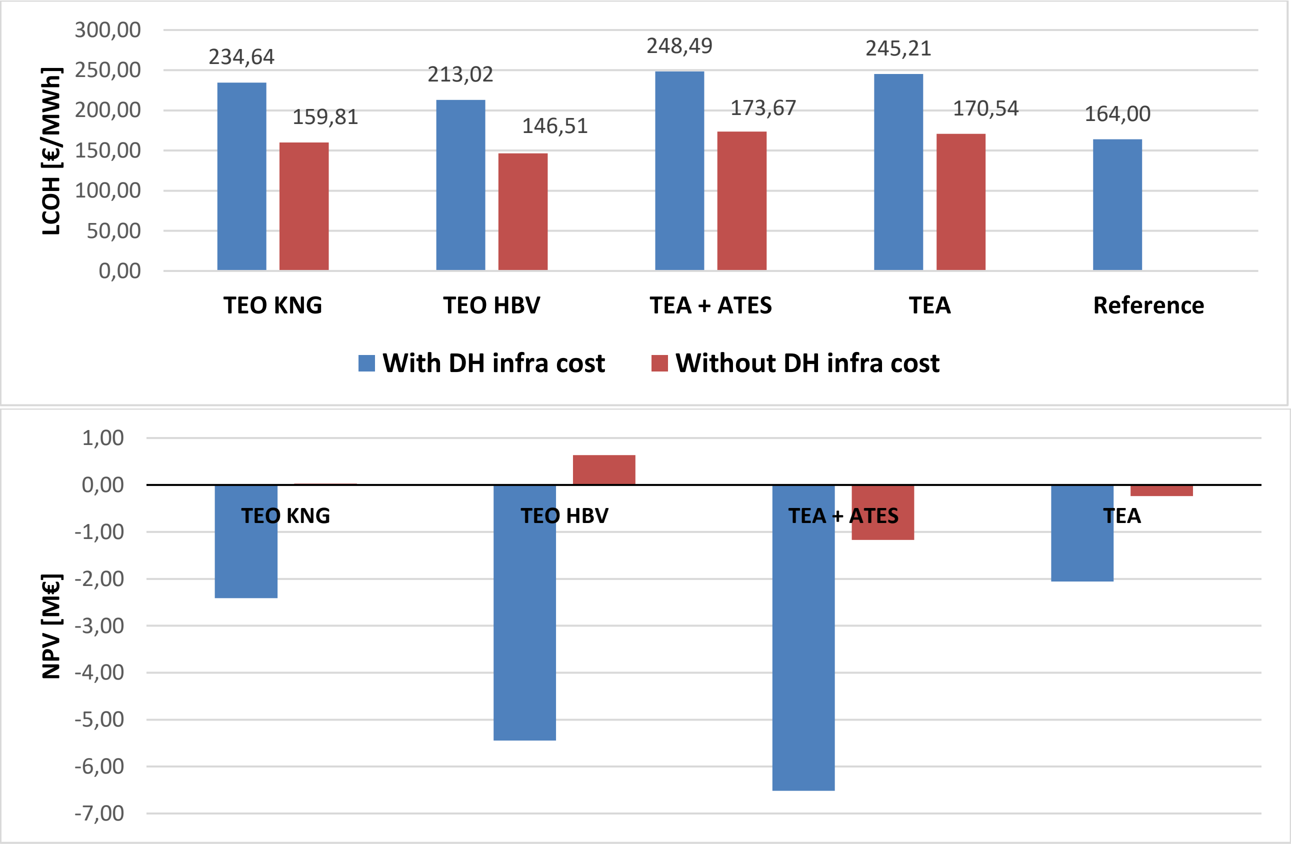


Figure 18a: LCOH and 14b) NPV of TEO and TEA scenarios with and without DH infrastructure cost

The uncertainty of the future price of natural gas was tested using four price scenarios and their effect on the cost of CO_2 avoided for each district heating scenario. The price of natural gas determines for a large part the LCOH of the reference scenario with an individual natural gas boiler. A higher gas price will mean that it is relatively cheaper to switch to a system without natural gas use, and thus will the relative costs of the avoided CO_2 by such a system be lower. Figure 19 shows the variation of these costs for each scenario, for the different price levels. It can be seen that the price of gas has high influence on the attractiveness of the district heating systems. For each change in price level, the difference in emission avoidance cost is roughly 70-100 €/tonne. However, for all TEO and TEA scenarios the costs per tonne CO_2 avoided remain very unattractive even in the highest natural gas price scenario. Only the TEO HBV scenario would potentially be eligible for subsidy according to the present SDE++ regulations (RVO, 2020d).

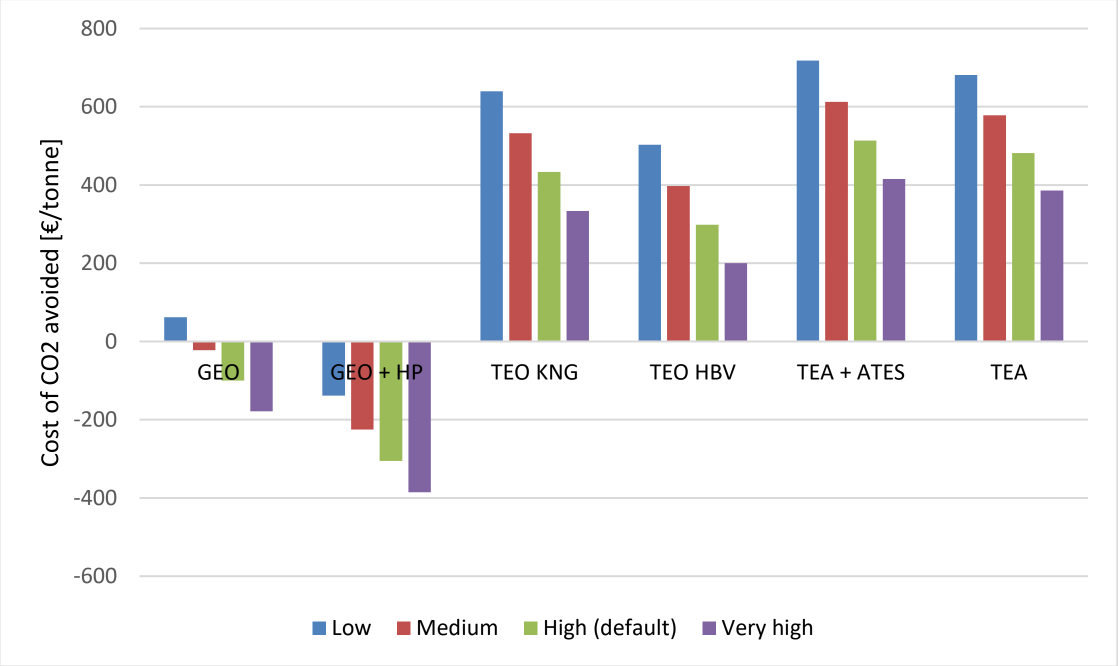


Figure 19: Effect of price of natural gas (2030) on costs of CO_2 avoided per scenario

The volatility of the large-consumer electricity price by 2030 (and onwards) poses a lot of uncertainty for the economic performance of the district heating systems. Especially for the systems that include a heat pump, that use large amounts of electricity for their heat production, the electricity price is an important factor in their financial performance. At a price difference of 40%, LCOHs will change 5-10% and NPVs up to 35%.

The value of the *discount rate* handled for geothermal DH is found to have a very strong influence on the profitability (NPV) of the project. A higher value of 9%, as assumed by for example [source], would vanish the entire profit margin of the scenario without heat pump, while a discount rate of two percent point lower would double the NPV's in both scenarios. If the social discount rate of 3% would be assumed, like in the other DH scenario's, the NPV's would increase with at least €50M in both scenarios. This effect due to the high annual revenues of the systems. For the TEO DH scenarios, a change in discount rate has much less effect, which can be explained by the much lower annual profits of the projects. The choice of discount rate in reality depends mostly on the expectations regarding return on investment of the main investor.

In all scenarios, the influence of a change in CAPEX was found to be more significant than a change in OPEX. Both LCOH and NPV showed larger changes for CAPEX for an equal percentual change. However, the impact of a change in CAPEX is distorted by the fact that the annual OPEX is often a percentage of the initial CAPEX, so that the OPEX also decreases when the CAPEX are lower. In reality, lower CAPEX for the same technology will likely not mean that the OPEX of that technology will be proportionally lower.

To achieve comfortable living temperatures in the homes, a supply temperature of 70 degrees Celsius should be high enough. However, if this temperature prove to be insufficient, due to for example larger than expected losses or lower insulative values, higher temperatures will be needed. For DH systems with a collective heat pump, this will mean that the COP of the heat pump will decrease, leading to larger electricity consumption, higher LCOHs and higher emission factors. This in turn leads to higher costs of avoided CO_2, as is displayed in figure 16.

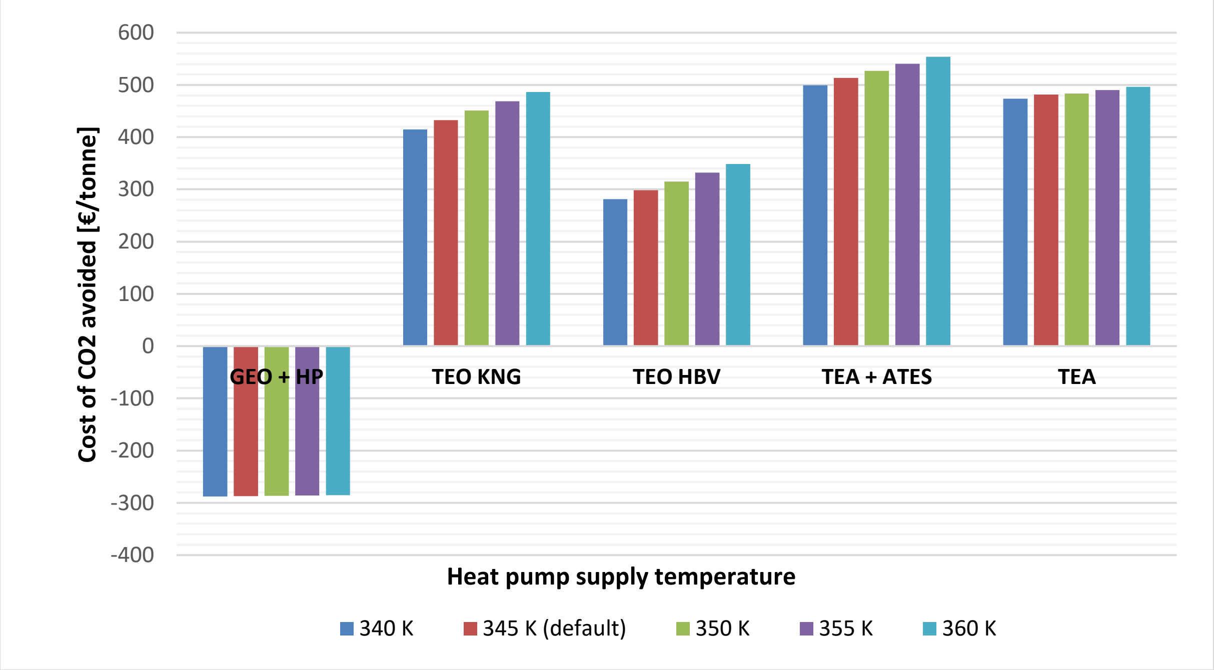


Figure 20: Effect of supply temperature on costs of CO_2 avoided per scenario

Changes in the efficiency of heat pumps as percentage of the maximum Carnot efficiency are found to have similar effects of the costs of CO_2 avoided. This efficiency determines the COP of the heat pumps at a given input and output temperature. Improving the efficiency to 70%, which would raise the COP of a 15-70 ºC heat pump from 3.5 to 4.1, thereby reducing electricity consumption and lowering LCOH and emission factors. Although the effect on LCOHs is limited (a few percent change at most), the emission avoidance cost are improved more significantly. This applies mostly to the TEO and TEA scenarios. Figure 21 shows these effects.

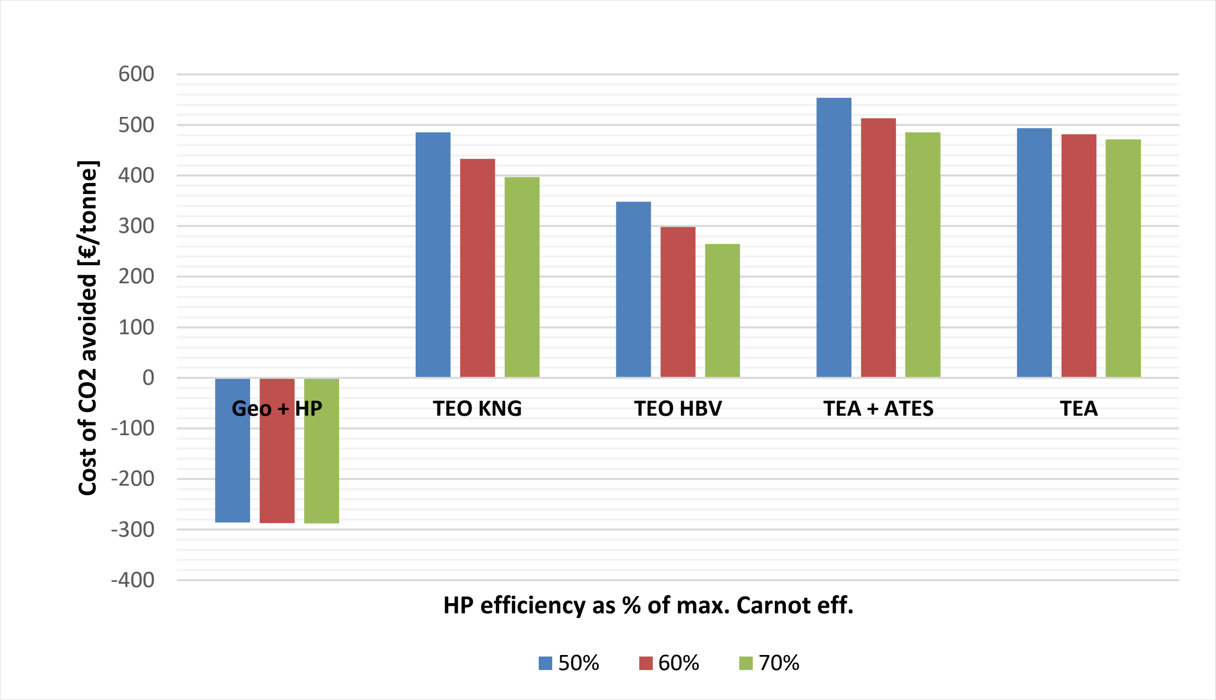


Figure 21: Effect of heat pump efficiency on costs of CO_2 avoided per scenario

6. Discussion

In this chapter, the obtained results from the various district heating models are placed into context of previous studies. The implications of these findings for the practical implementation of the studied systems for Benoordenhout and similar districts are discussed and recommendations are made regarding the application and usefulness of the systems. Thereafter, the methods and results of this research are critically reflected upon and the main uncertainties and limitations herein are highlighted. Finally, recommendations are made for further research to mitigate these limitations, to sharpen the findings of this research and to expand the knowledge on the field of sustainable district heating.

6.1 Results and implications

Geothermal energy for district heating

The levelized cost of heat of the geothermal district heating systems were found to be very low, at 143 €/MWh without heat pump and 106 €/MWh for the combination with heat pump cascading. Comparison of these results with similar studies is difficult, as the energetic potential of a geothermal system is highly dependent on physical properties of the subsurface, which have a high geographic variability. Most international studies regarding geothermal energy for direct-heat purposes have focused on high-enthalpy aquifers, producing pressurized water >100ºC (Beckers et al., 2014). Research on the economic performance of low-enthalpy aquifer utilization has been limited thus far, so the results of this study can contribute to filling the knowledge gap regarding geothermal energy utilization for MT district heating. In the Netherlands, there are no geothermal district heating systems currently in operation, to which the performance can be measured. The calculated LCOHs in this study are considerably lower than the value of 360 €/MWh Daniilidis, Alpsoy & Herber (2017) found for a potential geothermal district heating system in Groningen, but their system focused on an aquifer layer at 4000 meters depth, twice as deep as the Jurassic sandstone layers used for the geothermal system in Benoordenhout. Moreover, the effective capacity of the doublet in Groningen was at least 5 MWth lower.

The low LCOH that can be achieved in The Hague is mainly due to the very favorable conditions of the subsurface of Zuid-Holland, with thick, highly permeable aquifer layers at relatively shallow depth. Under these circumstances, high flow rates and subsequently high thermal capacities can be achieved while drilling costs are limited. These circumstances are exceptional for the Netherlands, which is why systems of comparably low cost of heat can most likely not be achieved in most parts of the country. One of the goals of this case study was to provide an example for similar old urban neighborhoods. Unfortunately, the results of this geothermal district heating system model will only be reasonably applicable for neighborhoods in cities within the same region, such as Delft, Leiden, Rotterdam, Dordrecht and other parts of The Hague. And even though the geothermal potential in this region is high, Willems & Nick (2019) stress the importance of a regional ‘master-plan’ approach instead of a ‘first come, first serve’ basis for individual projects that will lead to interference and inefficient use of the valuable heat resources. The Malieveld doublet as studied in this research should thus only be developed if it can be included in a greater, region-wide system of optimized geothermal heat locations and not only to fulfill the demands of Benoordenhout.

TEO and TEA for district heating

The potential of district heating systems based on thermal energy from wastewater or surface water are found to be not nearly large enough to supply the entire neighborhood of Benoordenhout. For most older urban neighborhoods, the potential of these sources will be limited, unless the neighborhoods happens to be situated near a WWTP or large body of water. Furthermore, the costs of the district heating infrastructure are large compared to the annual revenues that the sources of TEO and TEA can generate. Because of this, the NPVs of the four studied systems are negative and LCOH high. This implicates that district heating systems based on TEO or TEA are not very suitable to replace current residential heat systems. However, these technologies can be more useful when the required heat grid is less complex, for example when all the heat is used by a single or a few large consumers like offices or swimming pools, instead of a larger group of residential consumers. This way, the costs of DH infrastructure will be less pressing on the financial result, and can energy from wastewater and surface water make a sustainable and economically interesting contribution to the heat system. This can be the case in Benoordenhout as well. Large utility buildings in Benoordenhout are for example the Shell headquarters, close to the TEO location at the Koninginnegracht, or the HMC Bronovo hospital in the north of the district. Another scenario in which TEO and TEA could become a cost-effective energy source, is when a larger open DH heating system would be developed, to which multiple suppliers can enter. In that case, the heat infrastructure would not be placed solely for the TEO/TEA source, but shared with other (larger) heat suppliers, like industrial waste heat producers or geothermal sources. The Heat Roundabout (*Warmterotonde*) in the province Zuid-Holland that is currently in development, is planned to become such an open heat network and can provide perspective for the application of TEO and TEA for district heating (Provincie Zuid-Holland, n.d.).

Consumer value of connection to DH system

For the customer, it is presently not desirable to switch from a natural gas boiler to district heating. The current fees for district heating are so high that the potential savings on natural gas expenses, even with the expected gas price increase, are not enough to make for a profitable investment. The maximum costs for district heating are currently coupled to the estimated price of heating with a natural gas boiler. However, this ‘punishes’ users of DH systems when the government imposes higher taxes on natural gas. Moreover, although the ‘per-GJ’ price of district heat is equal to the cost of natural gas, the actual cost of district heating is considerably higher, due to several additional fees adding up to hundreds of euros annually. This is reflected in the negative NPV and higher than reference consumer LCOH of district heating, and is a widely shared experience among current Dutch district heating customers (Consumentenbond, 2019; Stadsverarming, 2015). To make district heating systems an economically interesting alternative for natural gas from the viewpoint of the consumer, a decoupling of the prices for natural gas and district heating is required. Furthermore, subsidies are needed to cover the high connection fee for district heating networks, to stimulate a faster transition away from natural gas.

6.2 Critical reflection and limitations

Uncertainty in cost of district heating

In all studied district heating scenarios, the largest cost factor is not the heat source itself, but the construction of the district heating system. Accurate estimation of these cost is thus crucial in the economic analysis of a proposed system. Initially, the Vesta MAIS model was aimed to be used for DH cost calculation in this study, but with the methods from said model, unusually high costs per meter were found in preliminary calculations, that did not compare to cost of existing district heating systems. It was therefore decided to adopt the method used by Ecofys (Menkveld et al., 2015, pp. 88-89), in which the cost of DH infrastructure (per kW required capacity) were estimated average values from existing DH systems, discerned in categories based on size and building density. Although the method from Ecofys is more simplified than the methods from Vesta calculation, it is believed that the resulting cost figures represent a more realistic estimation.

Changes to parameters that influence DH costs have a large effect on the financial results. The specific costs of DH infrastructure are an obvious factor in this, impacting the infrastructure costs directly, but other factors have a large indirect effect. In the sensitivity analysis, the *simultaneity factor* of the demand was found to have large influence on the LCOH and NPV in all scenarios. A higher simultaneity factor means that peak heat demands have more overlap, which will require the heat infrastructure to have a higher capacity. The costs of DH infrastructure are determined per kW capacity, so higher simultaneity will drastically increase the costs for heat infrastructure. The actual simultaneity of heat demand depends on several factors, most importantly the number of individual consumers and the insulation capacity of the connected buildings, and can vary significantly between different neighborhoods (Simon Bos, personal communication). As both Vesta and Menkveld et al. (2015) use values between 0.53-0.55 for district-size heat systems with low-medium insulated buildings, the confidence in this value is fairly high but to obtain more accurate information on heat demand simultaneity of existing neighborhoods, gas demand profiles with short time intervals should be studied.

More uncertainty arises in the heat *loss factors* occurring in distribution. The loss factors assumed in this study, 10% for TEO/TEA and 20% for the geothermal system, were estimated based on the size and transport distance of the systems and literature examples from other systems. The exact percentage of heat lost in distribution depends of several circumstances, and is often only known after completion of the DH system. However, this factor has a large influence the required infrastructure capacity and thus DH cost. Larger than expected losses mean a lower supply temperature at the end consumer, less heat sold and consequently lower annual revenues. This considered, underestimation of the loss factor is very undesirable. Especially for the geothermal scenarios, a higher loss factor can significantly impact the LCOH, and could mean the difference between a positive and negative NPV and a LCOH higher than reference for the scenario without HP. More exact modelling of the expected loss factor, and possibly a safety margin, are thus highly recommended for the development and economic analysis of a proposed DH system.

Supply temperature

In this study, it is assumed that a supply temperature of 72 ºC is sufficient to accomplish comfortable living temperatures in the connected homes. However, on the coldest days of the year, or due to higher than expected heat losses, this temperature level might be insufficient. For heat pump based district heating, this problem can be solved by adjusting the supply temperature at the cost of a lower COP. A geothermal system (without heat pump) however, is restricted by the extraction temperature of the well. In that case, a solution can be to combust natural gas extracted from the brine to achieve higher supply temperatures. Geothermal brine in the Netherlands generally contains about 1 m^3 of natural gas for each m^3 of geothermal fluid. At a flow rate of 500 m^3/h, 15 GJ/h worth of natural gas is pumped up, that could achieve a supply temperature increase of around 7 degrees using a boiler. However, this would significantly increase the emission factor of the delivered heat. Another possibility is to add a heat pump directly after the geothermal heat exchanger to upgrade supply temperatures (Vrijlandt et al., 2019; Jensen, Ommen, Markussen & Elmegaard, 2017).

6.3 Recommendations for further research

The geothermal district heating model in this study included a scenario in which a heat pump is added to the return flow of the DH network. This scenario was adopted from Vrijlandt et al. (2019), where the application of a heat pump is suggested to maximize the heat extraction from the well. Under the operative assumptions in this study, the economic and energetic benefits of the heat pump addition were found to be very large. However, the application of such a system has not been done often in reality, which limits the knowledge from earlier experience. Further knowledge from field testing is required to make more accurate estimations on the performance of heat pump cascading in geothermal systems.

Heat demand of residential buildings is often highly variable, and can displays strong peaks and drops during the day and year. In a district heating system, the heat source needs to be able to operate flexibly as well, especially when the heat storage capacity is limited, and when demand peaks exceed the capacity of the main heat source, back-up systems need to be deployed. In follow-up research, a software package like EnergyPRO could be used to dynamically match heat supply and demand in the district of Benoordenhout. Furthermore, this software could be used to test and optimize the use of thermal energy storage and its effect on peak supply capacity and LCOH.

This study covers only the CO_2 emissions during the use-phase of the studied heat technologies. However, potentially significant emission volumes occur in the construction and end-of-life, and can come from compounds other than CO_2. For example, special attention should go out to the refrigerant used in the heat pumps, as some refrigerants are extremely harmful when released into the environment. To fully assess the real emission reduction potential of the studied heat systems, a full life-cycle analysis (LCA), including production of the heat technologies, construction of the DH network and decommissioning of the materials could be conducted and compared to a LCA of the reference system.

This research is focused primarily on the physical/energetic side of the district heating topic, but the social side of the problem is equally critical. Participation of residents is a crucial factor in the implementation of district heating systems. The deployment of district heating systems will not be viable if the participation rate of residents in the designated district is too low. The aforementioned high cost of district heating is an important barrier to adoption, but there are more barriers that limit the willingness of civilians to connect to a district heating system. These can be for instance lack of perceived urgency, lack of perceived benefits or knowledge gaps. Research into (the stimulation of) civil participation in heat networks is already an active field of research and will be increasingly required as district heating is foreseen to grow into a prominent role in the future energy system.

7. Conclusions

To accommodate a shift away from the use of natural gas in the near future, the Dutch built environment is facing drastic reforms in its heat system. This brings about many challenges, especially for existing neighborhoods. The goal of this study is to provide more knowledge and insight into potential collective heating systems based on renewable energy sources, that are suited for older urban neighborhoods. The main research question to this end was:

How to identify the best suited collective heating system for an older urban neighborhood, in terms of resource availability and economic and environmental performance?

This question was approached by performing a case study on the neighborhood Benoordenhout in The Hague. An economic and environmental assessment was made on three potential heat sources for a medium-temperature district heating systems. The heat sources were thermal energy from surface water, thermal energy from waste water and geothermal energy. For the surface water and wastewater source, aquifer thermal energy storage can be applied and large-scale heat pumps will upgrade the heat input to required levels. For each heat source, two scenarios are developed, making a total of six heat scenarios for Benoordenhout, assessed over the period 2030-2050. These scenarios were compared to a reference scenario, in which residents continue to use an individual natural gas boiler until 2050.

Using a simulation dataset on heat demand of various house typologies and with data on building stock in the neighborhood, the average annual heat demand and peak demand the houses in Benoordenhout in 2030 were estimated. For each of the three heat sources, one or two main extraction locations were identified. The heat extraction potentials of the three sources were estimated by use of online data tools and consultation with experts. Data on capital and operational expenditure was obtained from literature and reports of existing DH systems. Methods on district heating construction cost estimations were obtained from literature and Vesta. Projections on future prices of electricity and natural gas, based on existing and expected policy were used. All data and methods were ultimately integrated into an energy model in Excel, to assess the economic and environmental performance of the six heat scenarios.

The annual heat demand of an average district household in 2030 was found to be 10.72 MWh, with a peak demand of 14.3 kW. The heat demand of the district will be close to 80 GWh annually, with a peak demand of 70 MW. It was found that only the heat potential of the geothermal system is large enough to supply the entire district, while in the heat scenarios including TEO and TEA, only 1.7% to 5.7% of households in the district can be supplied. For the geothermal system, connection with the existing DH network in The Hague is required to meet peak demands and to sell surplus heat.

The geothermal scenarios with and without heat pump cascading can generate significant NPVs of 31.7M€ and 16M€,respectively. Their LCOHs of 106 €/MWh and 142 €/MWh are lower than the cost of heat in the reference scenario (164 €/MWh). These result also indicate that the application of a heat pump to the return flow of geothermal DH can boost heat production and profits. All TEO and TEA scenarios are found to yield negative NPVs of several millions, so that substantial subsidies will be required to break even. The LCOH of heat of these scenarios are considerably higher than the reference LCOH.

All scenarios achieve significant reductions in the emission factor their produced heat, with reductions of 76-97%. However, in the TEO and TEA scenarios, most houses must find alternative heat sources to become independent of natural gas. The reduction in emission factor and LCOH in the geothermal scenarios is such, that the cost of avoided CO_2 is negative, meaning that the systems can save both cost and emissions compared to the reference scenario. Geothermal energy is therefore a very suited heat source for district heating of older urban neighborhoods. For the other four scenarios, these costs amount to hundreds of euros per avoided tonne, making those systems very unsuited to become the prime alternative to natural gas based heating.

For the consumer, connection to a district heating system is proven to remain very unattractive financially as long the current maximum prices remain. (Legally) lowering the prices for DH compared to natural gas is a crucial prerequisite to change this situation.

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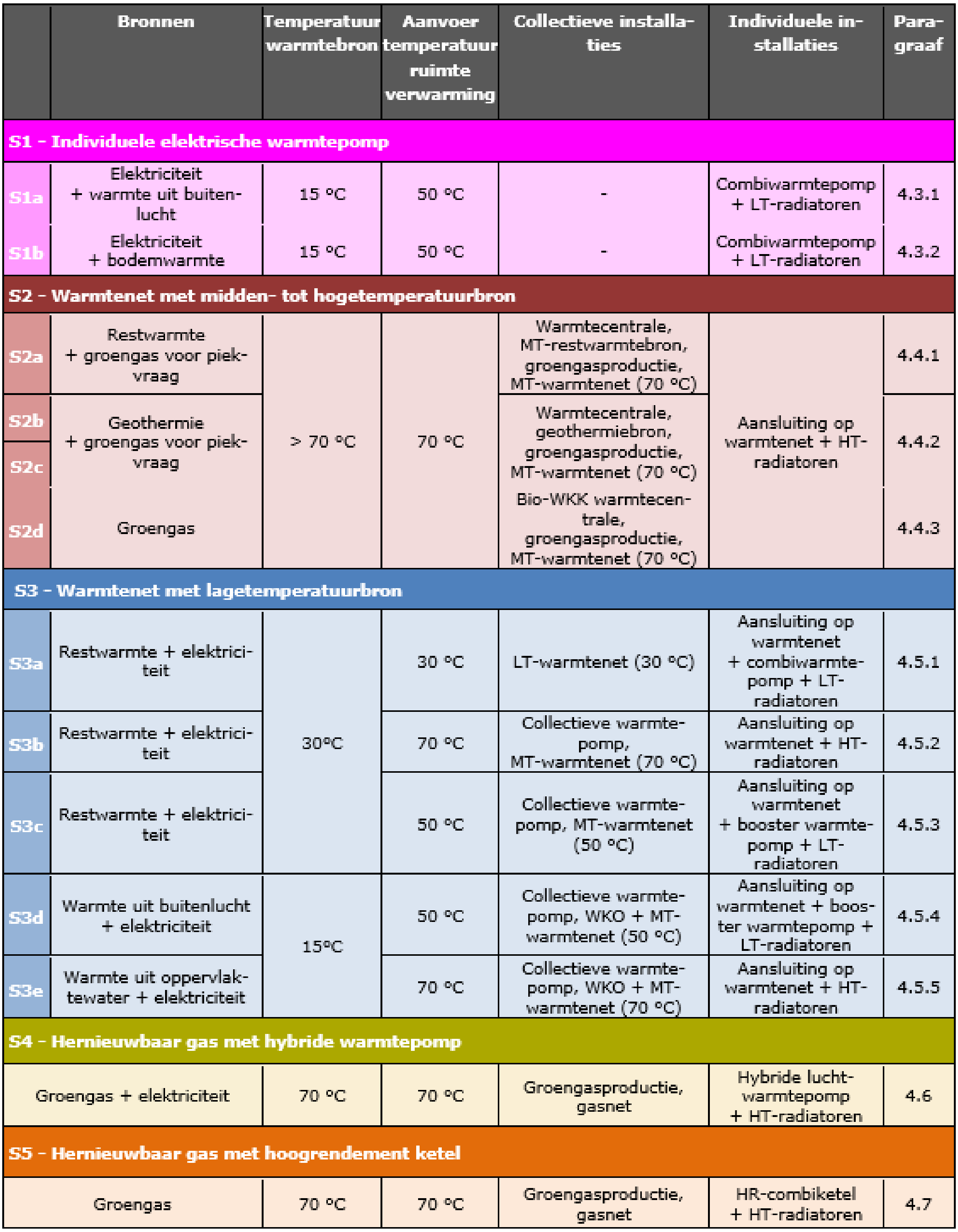
Appendix 1: Scenarios PBL Startanalyse Leidraad

This table is obtained from Hoogervorst et al. (2019)



	Bronnen	Temperatuur warmtebron	Aanvoer temperatuur ruimte verwarming	Collectieve installaties	Individuele installaties	Paragraaf
S1 - Individuele elektrische warmtepomp						
S1a	Elektriciteit + warmte uit buitenlucht	15 °C	50 °C	-	Combiwarmtepomp + LT-radiatoren	4.3.1
S1b	Elektriciteit + bodemwarmte	15 °C	50 °C	-	Combiwarmtepomp + LT-radiatoren	4.3.2
S2 - Warmtenet met midden- tot hogetemperatuurbron						
S2a	Restwarmte + groengas voor piekvraag	> 70 °C	70 °C	Warmtecentrale, MT-restwarmtebron, groengasproductie, MT-warmtenet (70 °C)	Aansluiting op warmtenet + HT-radiatoren	4.4.1
S2b **S2c**	Geothermie + groengas voor piekvraag			Warmtecentrale, geothermiebron, groengasproductie, MT-warmtenet (70 °C)		4.4.2
S2d	Groengas			Bio-WKK warmtecentrale, groengasproductie, MT-warmtenet (70 °C)		4.4.3
S3 - Warmtenet met lagetemperatuurbron						
S3a	Restwarmte + elektriciteit	30°C	30 °C	LT-warmtenet (30 °C)	Aansluiting op warmtenet + combiwarmtepomp + LT-radiatoren	4.5.1
S3b	Restwarmte + elektriciteit		70 °C	Collectieve warmtepomp, MT-warmtenet (70 °C)	Aansluiting op warmtenet + HT-radiatoren	4.5.2
S3c	Restwarmte + elektriciteit		50 °C	Collectieve warmtepomp, MT-warmtenet (50 °C)	Aansluiting op warmtenet + booster warmtepomp + LT-radiatoren	4.5.3
S3d	Warmte uit buitenlucht + elektriciteit	15°C	50 °C	Collectieve warmtepomp, WKO + MT-warmtenet (50 °C)	Aansluiting op warmtenet + booster warmtepomp + LT-radiatoren	4.5.4
S3e	Warmte uit oppervlaktewater + elektriciteit		70 °C	Collectieve warmtepomp, WKO + MT-warmtenet (70 °C)	Aansluiting op warmtenet + HT-radiatoren	4.5.5
S4 - Hernieuwbaar gas met hybride warmtepomp						
	Groengas + elektriciteit	70 °C	70 °C	Groengasproductie, gasnet	Hybride luchtwarmtepomp + HT-radiatoren	4.6
S5 - Hernieuwbaar gas met hoogrendement ketel						
	Groengas	70 °C	70 °C	Groengasproductie, gasnet	HR-combiketel + HT-radiatoren	4.7

Appendix 2: Calculation of TEO potential of water body

The capacity of a TEO system depends on the amount of heat that can be extracted from a body of water. The maximum extraction capacity of a surface water source can be calculated with the formula below (Syntraal, Stowa & Deltares, 2018).

$$P_{potential} = \left(\frac{|Q|\times \Delta T_{HE}\times \rho_w\times c_p}{10^6}\right) + \left(\frac{Z\times A\times \Delta T}{10^6}\right)$$

In which:

$P_{potential} = Heat\ extraction\ potential\ [MW]$

$|Q| = volume\ flow\ (direction\ independent)\ \left[{}^{m^3}/_{s}\right]$

$\Delta T_{HE} = maximum\ temperature\ difference\ [K]$

$\rho_w = density\ of\ water\left[\ 998\ {}^{kg}/_{m^3}\right]$

$c_p = heat\ capcity\ of\ water\ \left[4.195\ {}^{KJ}/_{kg\ *\ K}\right]$

$Z = heat\ transfer\ coefficient\ \left[{}^{W}/_{m^2\ *\ K}\right]$

$A = water\ surface\ area\ [m^2]$

$\Delta T = temperature\ increase\ from\ air\ [K]$

The second term in brackets in formula X only applies for (semi)-stagnant water bodies, where temperature increase by ambient air plays a significant role (Syntraal, Stowa & Deltares, 2018). As can be derived from the formula, the heat extraction potential of completely stagnant water bodies like ponds or small lakes is only dependent on the amount of heat exchange with the atmosphere, and thus merely depends on water surface area, and the volume of the water body. According to the methods from Syntraal, Stowa & Deltares (2018), three classifications of small stagnant water bodies can be used, based on their depth. For each of these classes, an estimation on extraction potential in GJ/m^2/year is made, based on average weather conditions in the Netherlands. The classes are listed in the table below:

Estimated energy potential of minor stagnant water bodies (Syntraal, Stowa & Deltares, 2018)

Depth	Heat extraction potential (GJ/m^2/y)
< 0.75m	0.216
0.75-3m	0.324
> 3m	0.432

Appendix 3: Energy price developments Vesta MAIS up to 2050

These tables are obtained from CE Delft (2019)

A: Electricity price developments Vesta for small and medium/large consumers

	CO_2/kWh	Elektriciteit (euro/kWh)						Elektriciteit (euro/kWh)					
	kg/kWh	Kleingebruik (<10.000 kWh/jr; LS)						(Klein) Middelgrote verbruikers					
Jaar		Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting	Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting
Jaar	RAT CO_2 KWH	KG COM_EXCL_CO_2	KG CO_2	KG DIS	KG TRANS	KG SDE	KG BEL_EL	KMG COM_EXCL_CO_2	KMG CO_2	KMG DIS	KMG TRANS	KMG SDE	KMG BEL_EL
2010	0,561	0,091	0,008	0,000	0,000	0,000	0,111	0,058	0,008	0,000	0,000	0,000	0,041
2020	0,561	0,096	0,016	0,000	0,000	0,028	0,111	0,075	0,016	0,000	0,000	0,010	0,041
2030	0,561	0,101	0,023	0,000	0,000	0,028	0,111	0,093	0,023	0,000	0,000	0,010	0,041
2040	0,561	0,101	0,023	0,000	0,000	0,028	0,111	0,093	0,023	0,000	0,000	0,010	0,041
2050	0,561	0,101	0,023	0,000	0,000	0,028	0,111	0,093	0,023	0,000	0,000	0,010	0,041

	CO_2/kWh	Elektriciteit (euro/kWh)						Elektriciteit (euro/kWh)					
	kg/kWh	Grootverbruik						Glastuinders					
Jaartal		Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting	Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting
Jaar	RAT_CO_2_KWH	GG COM_EXCL_CO_2	GG CO_2	GG DIS	GG TRANS	GG SDE	GG BEL_EL	GLAST COM_EXCL_CO_2	GLAST CO_2	GLAST DIS	GLAST TRANS	GLAST SDE	GLAST BEL_EL
2010	**0,561**	**0,058**	**0,008**	**0,000**	**0,000**	**0,000**	**0,011**	**0,058**	**0,008**	**0,000**	**0,000**	**0,000**	**0,041**
2020	0,561	0,075	0,016	0,000	0,000	0,010	0,011	0,075	0,016	0,000	0,000	0,010	0,041
2030	0,561	0,093	0,023	0,000	0,000	0,010	0,011	0,093	0,023	0,000	0,000	0,010	0,041
2040	0,561	0,093	0,023	0,000	0,000	0,010	0,011	0,093	0,023	0,000	0,000	0,010	0,041
2050	0,561	0,093	0,023	0,000	0,000	0,010	0,011	0,093	0,023	0,000	0,000	0,010	0,041

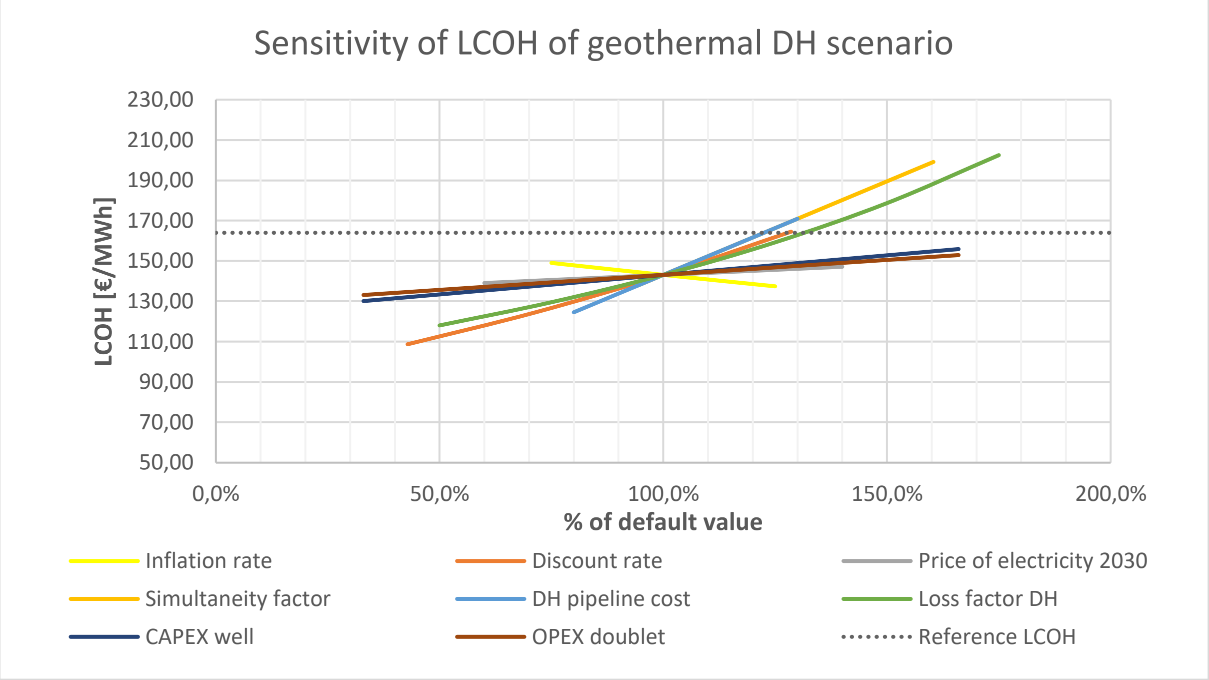
B: Gas price developments Vesta for small and medium/large consumers

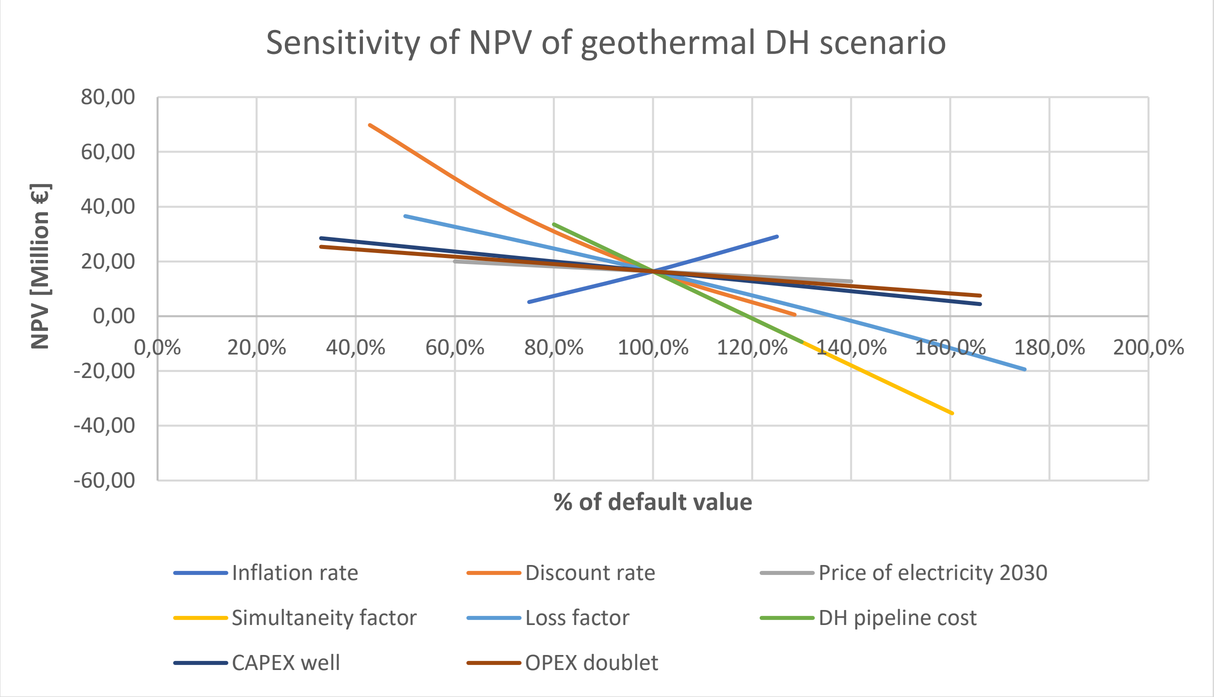
	CO_2/m^3	Gas (euro/m^3)						Gas (euro/m^3)					
	kg/m^3	Kleingebruik (< 5.000 m^3/jr; LD)						(Klein) Middelgrote verbruikers					
Jaar-tal		Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting	Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting
Jaar	RAT_CO$_2$_KWH	KG COM_EXCL_CO$_2$	KG CO_2	KG DIS	KG TRANS	KG SDE	KG BEL_EL	KMG COM_EXCL_CO$_2$	KMG CO_2	KMG DIS	KMG TRANS	KMG SDE	KMG BEL_EL
2010	1,78	0,375	0,000	0,000	0,000	0,000	0,163	0,184	0,000	0,000	0,000	0,000	0,141
2020	1,78	0,425	0,000	0,000	0,000	0,053	0,163	0,280	0,000	0,000	0,000	0,043	0,141
2030	1,78	0,456	0,000	0,000	0,000	0,053	0,163	0,351	0,000	0,000	0,000	0,043	0,141
2040	1,78	0,456	0,000	0,000	0,000	0,053	0,163	0,351	0,000	0,000	0,000	0,043	0,141
2050	1,78	0,456	0,000	0,000	0,000	0,053	0,163	0,351	0,000	0,000	0,000	0,043	0,141

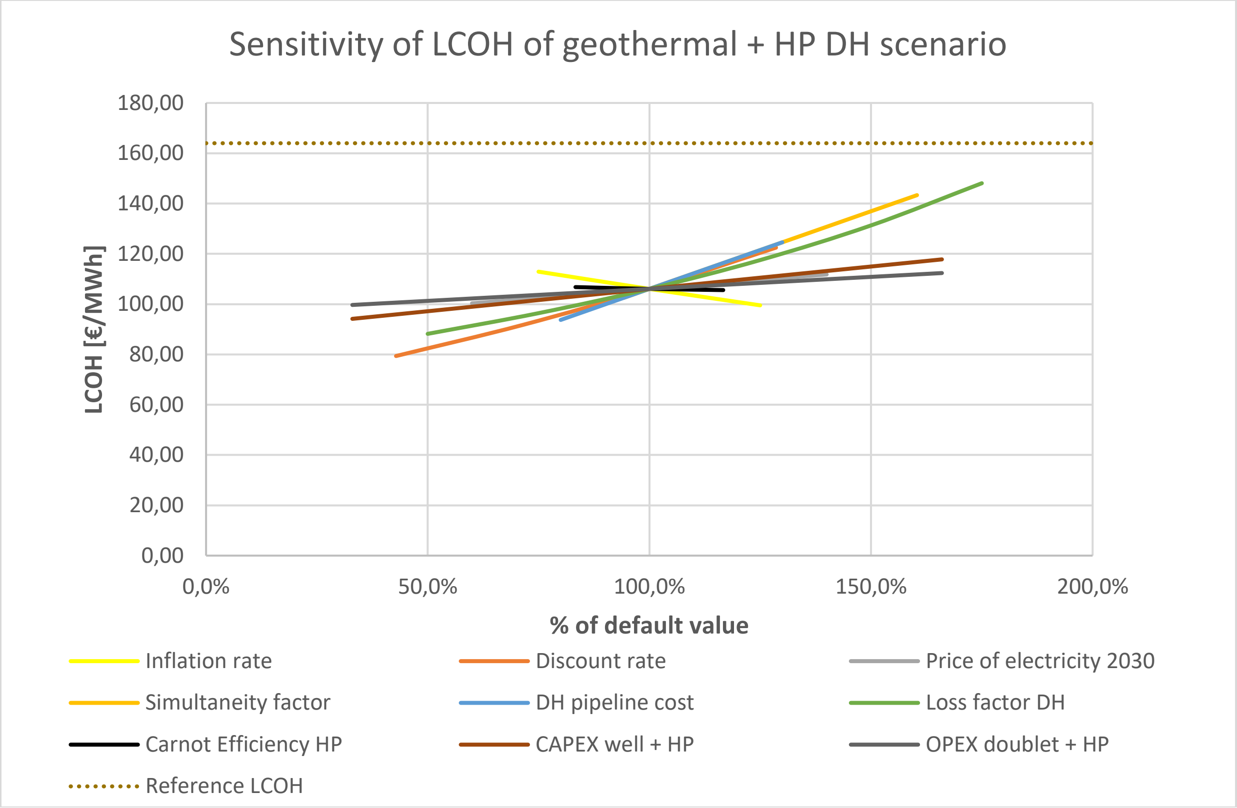
	CO_2/m^3	Gas (euro/m^3)						Gas (euro/m^3)					
	kg/m^3	Grootverbruik						Glastuinders					
Jaar-tal		Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting	Commodity excl. CO_2		Distributie	Transport en capaciteit	SDE-heffing	Energie-belasting
Jaar	RAT_CO$_2$_KWH	GG COM_EXCL_CO$_2$	GG CO_2	GG DIS	GG TRANS	GG SDE	GG BEL_EL	GLAST COM_EXCL_CO$_2$	GLAST CO_2	GLAST DIS	GLAST TRANS	GLAST SDE	GLAST BEL_EL
2010	1,78	0,184	0,000	0,000	0,000	0,000	0,012	0,184	0,000	0,000	0,000	0,000	0,024
2020	1,78	0,280	0,000	0,000	0,000	0,043	0,012	0,280	0,000	0,000	0,000	0,043	0,024
2030	1,78	0,351	0,000	0,000	0,000	0,043	0,012	0,351	0,000	0,000	0,000	0,043	0,024
2040	1,78	0,351	0,000	0,000	0,000	0,043	0,012	0,351	0,000	0,000	0,000	0,043	0,024
2050	1,78	0,351	0,000	0,000	0,000	0,043	0,012	0,351	0,000	0,000	0,000	0,043	0,024

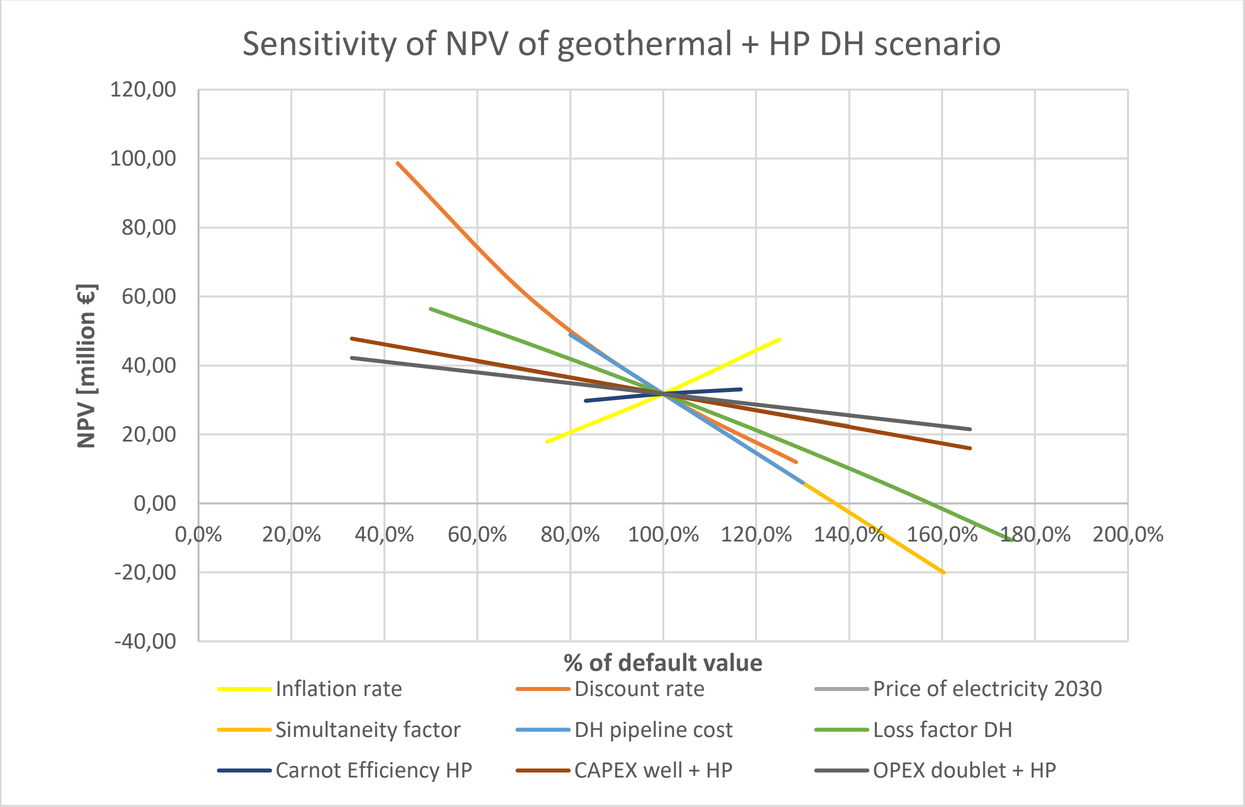
Appendix 4: Results of the sensitivity analysis

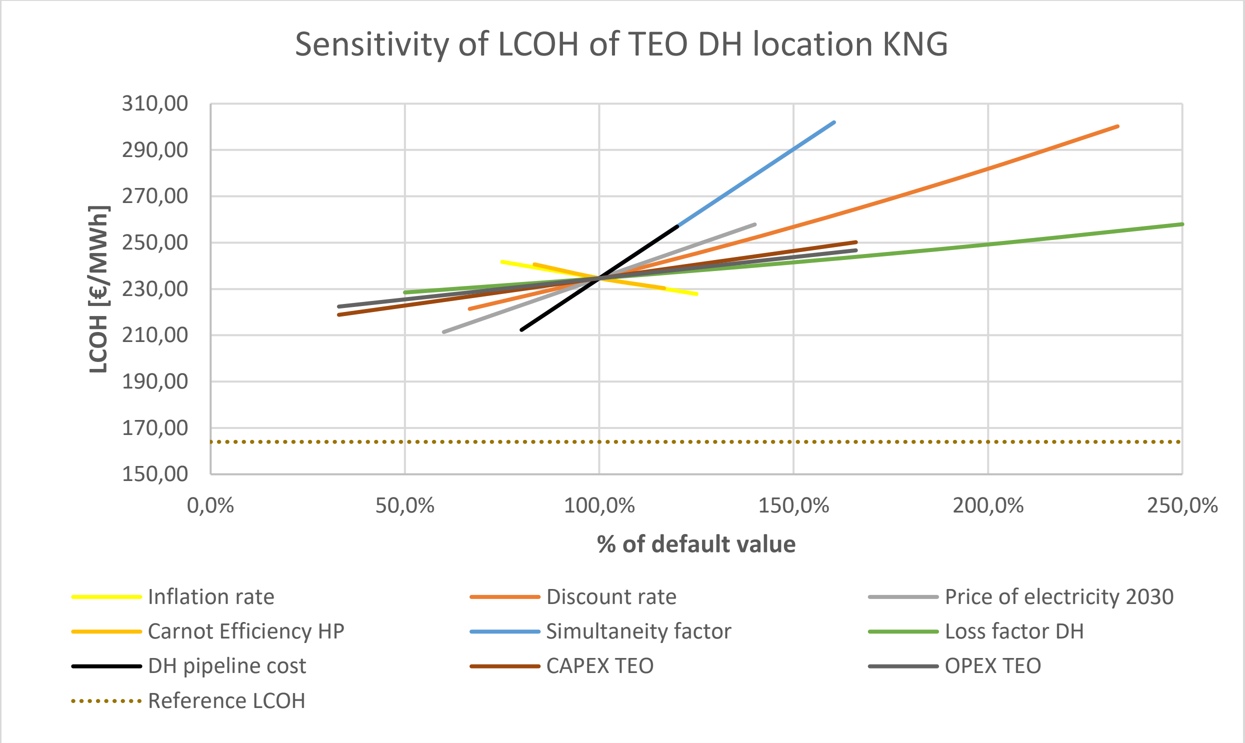
Below, the sensitivities of the LCOH and NPV of the six heat scenarios to changes in parameter values are displayed.

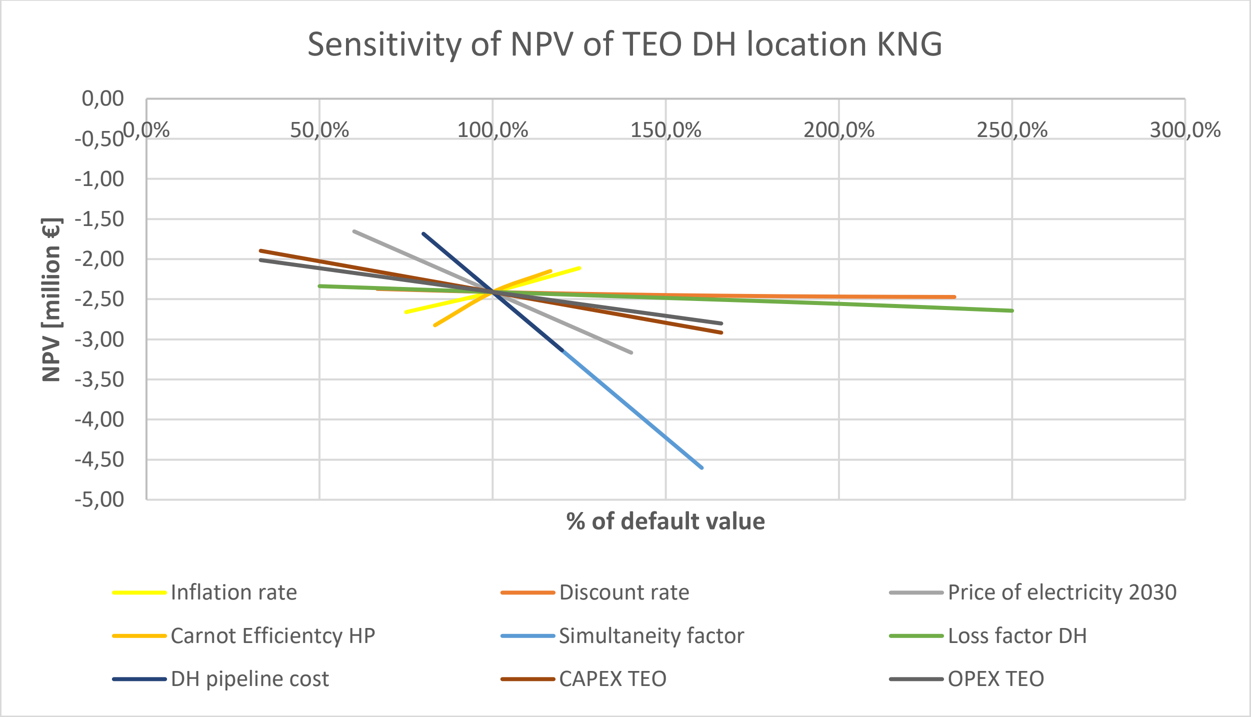


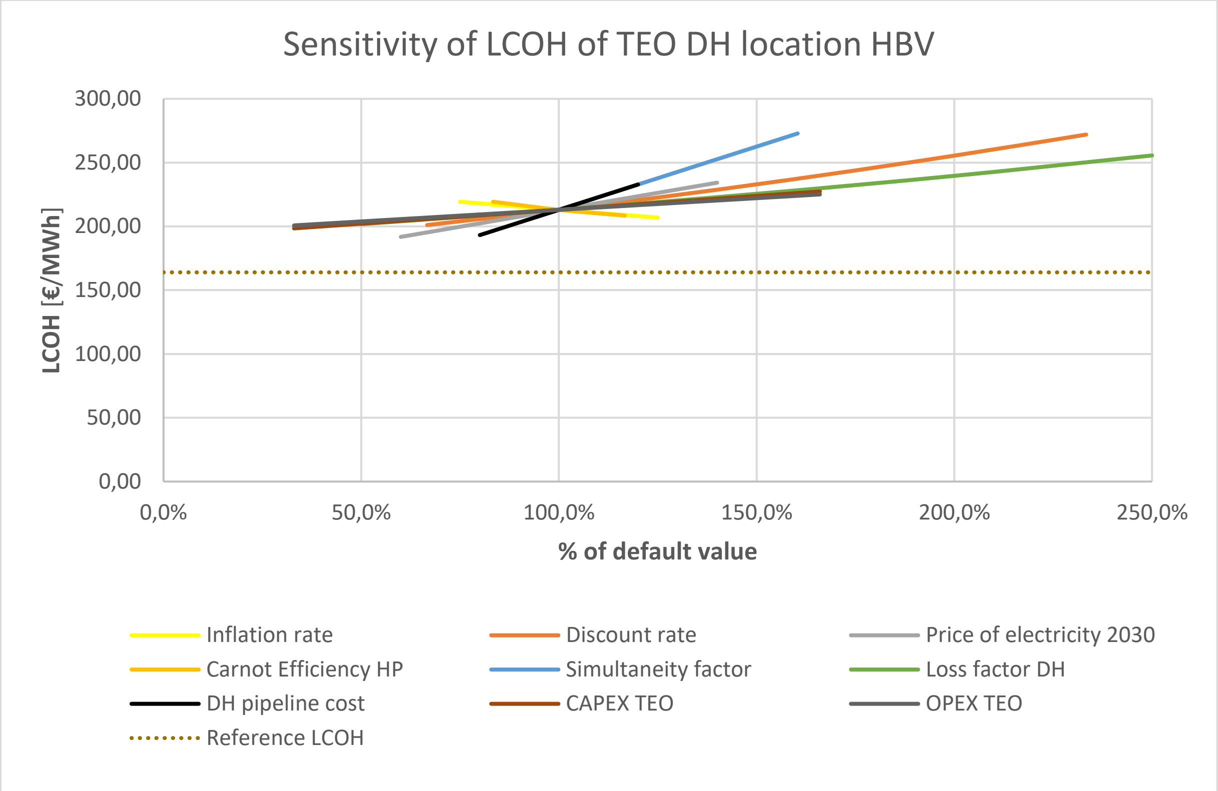


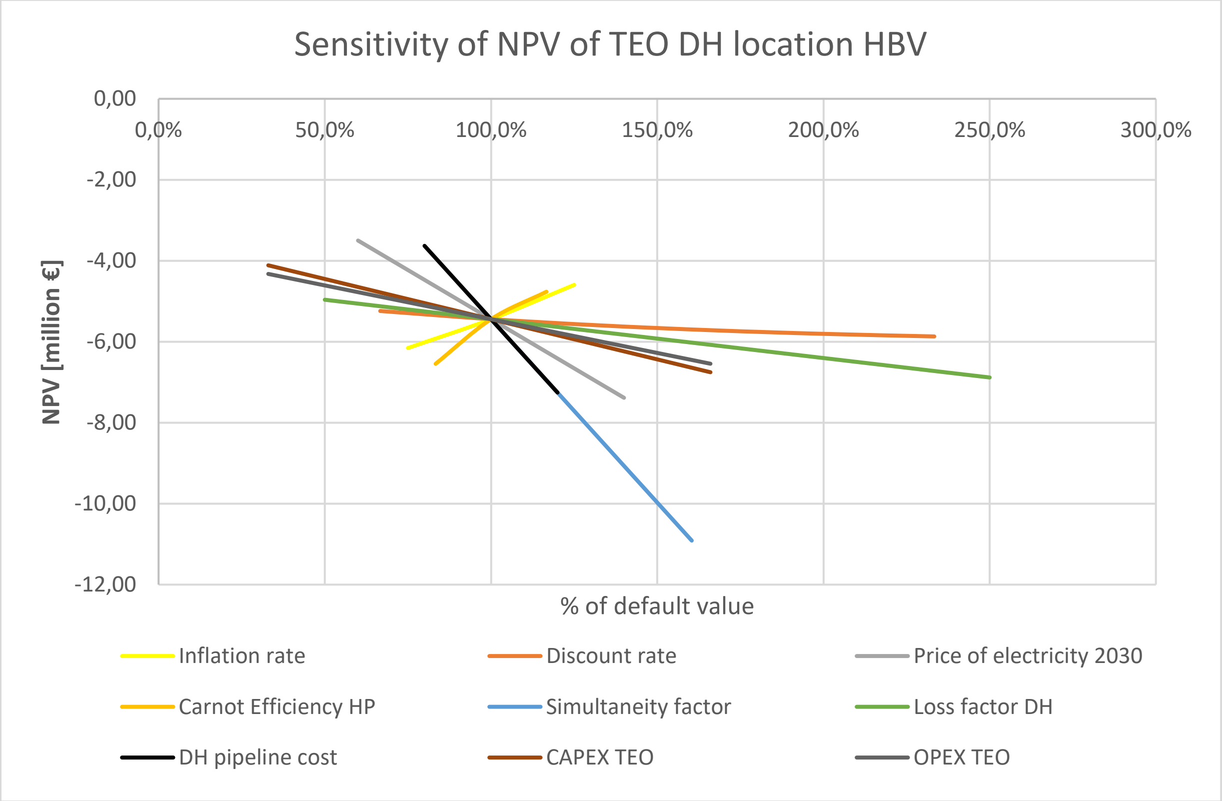

Sensitivity of LCOH of geothermal + HP DH scenario
LCOH [€/MWh]
180,00
160,00
140,00
120,00
100,00
80,00
60,00
40,00
20,00
0,00
0,0%
50,0%
100,0%
150,0%
200,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Simultaneity factor
DH pipeline cost
Loss factor DH
Carnot Efficiency HP
CAPEX well + HP
OPEX doublet + HP
Reference LCOH

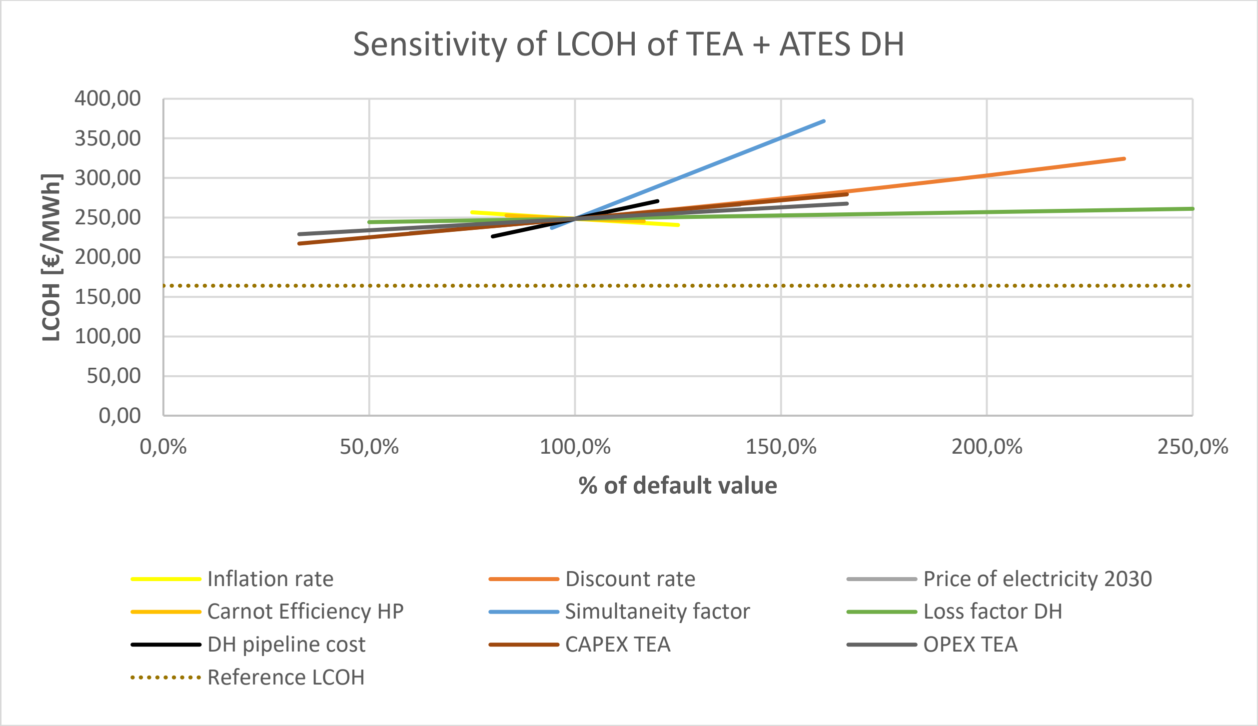

Sensitivity of NPV of geothermal + HP DH scenario
NPV [million €]
120,00
100,00
80,00
60,00
40,00
20,00
0,00
-20,00
-40,00
0,0%
20,0%
40,0%
60,0%
80,0%
100,0%
120,0%
140,0%
160,0%
180,0%
200,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Simultaneity factor
DH pipeline cost
Loss factor DH
Carnot Efficiency HP
CAPEX well + HP
OPEX doublet + HP

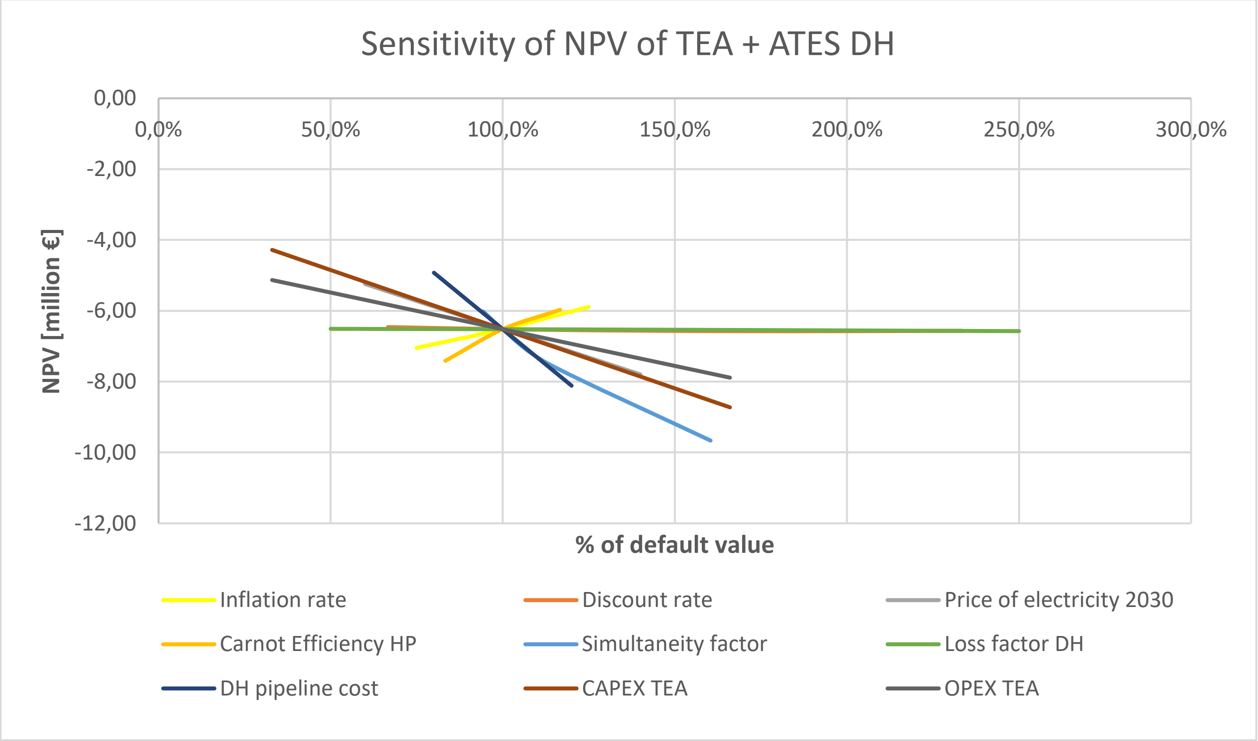

Sensitivity of LCOH of TEO DH location KNG
LCOH [€/MWh]
310,00
290,00
270,00
250,00
230,00
210,00
190,00
170,00
150,00
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficiency HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEO
OPEX TEO
Reference LCOH

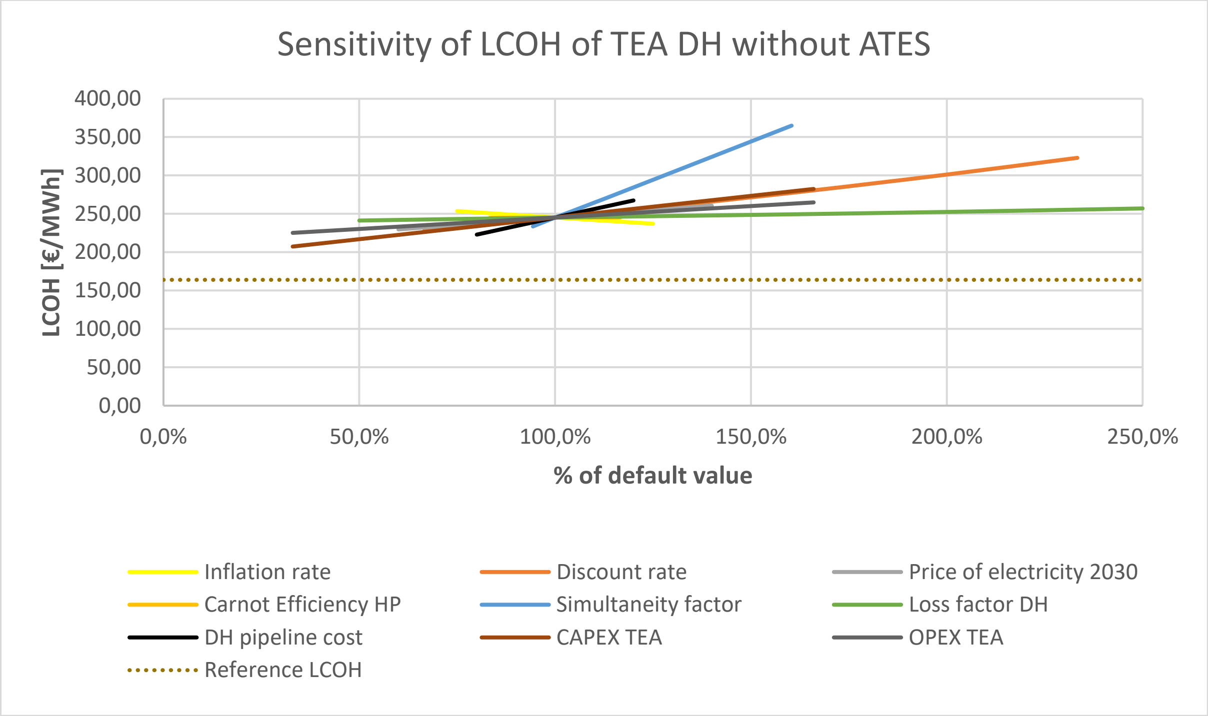

Sensitivity of NPV of TEO DH location KNG
NPV [million €]
0,00
-0,50
-1,00
-1,50
-2,00
-2,50
-3,00
-3,50
-4,00
-4,50
-5,00
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
300,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficientcy HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEO
OPEX TEO

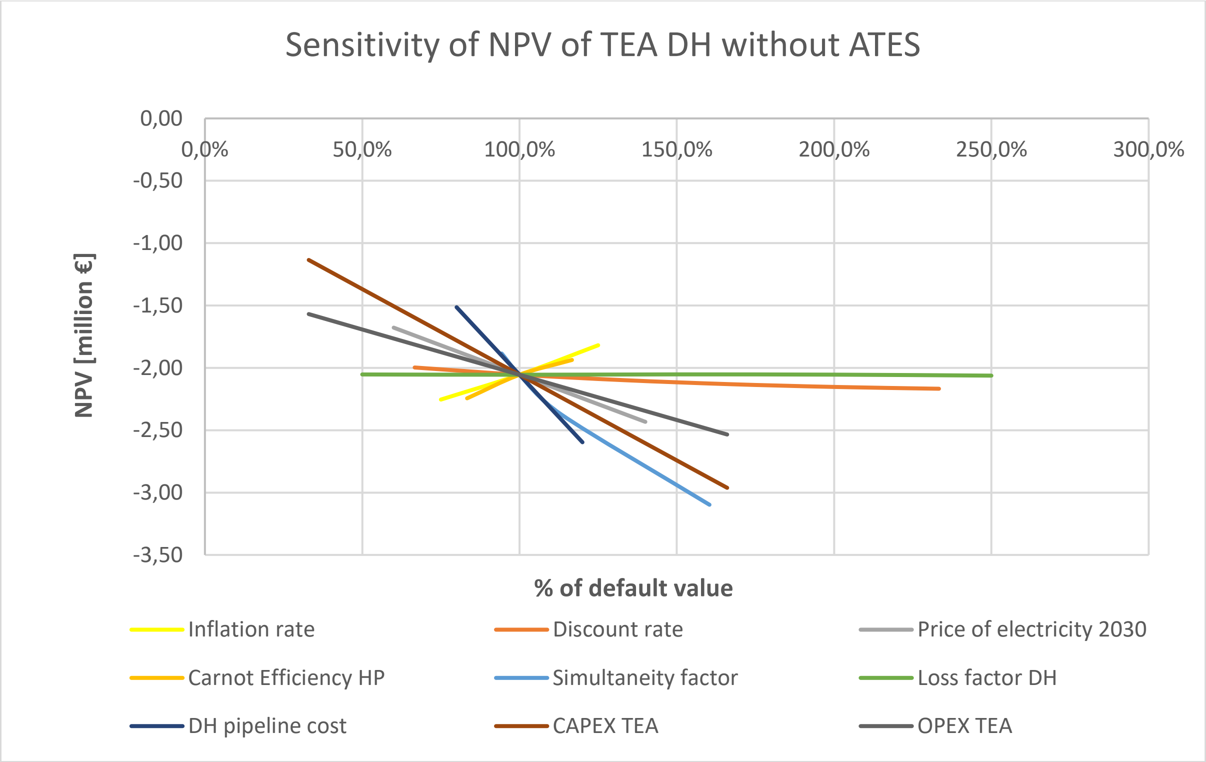

Sensitivity of LCOH of TEO DH location HBV
LCOH [€/MWh]
300,00
250,00
200,00
150,00
100,00
50,00
0,00
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficiency HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEO
OPEX TEO
Reference LCOH


Sensitivity of NPV of TEO DH location HBV
NPV [million €]
0,00
-2,00
-4,00
-6,00
-8,00
-10,00
-12,00
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
300,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficiency HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEO
OPEX TEO


Sensitivity of LCOH of TEA + ATES DH
LCOH [€/MWh]
400,00
350,00
300,00
250,00
200,00
150,00
100,00
50,00
0,00
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficiency HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEA
OPEX TEA
Reference LCOH


Sensitivity of NPV of TEA + ATES DH
NPV [million €]
0,00
-2,00
-4,00
-6,00
-8,00
-10,00
-12,00
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
300,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficiency HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEA
OPEX TEA


Sensitivity of LCOH of TEA DH without ATES
LCOH [€/MWh]
400,00
350,00
300,00
250,00
200,00
150,00
100,00
50,00
0,00
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficiency HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEA
OPEX TEA
Reference LCOH


Sensitivity of NPV of TEA DH without ATES
NPV [million €]
0,00
-0,50
-1,00
-1,50
-2,00
-2,50
-3,00
-3,50
0,0%
50,0%
100,0%
150,0%
200,0%
250,0%
300,0%
% of default value
Inflation rate
Discount rate
Price of electricity 2030
Carnot Efficiency HP
Simultaneity factor
Loss factor DH
DH pipeline cost
CAPEX TEA
OPEX TEA